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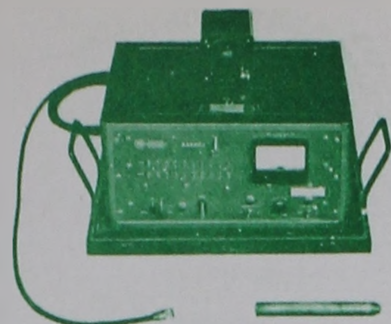

SOIL-MOISTURE MEASUREMENT

Howard W. Lull
and
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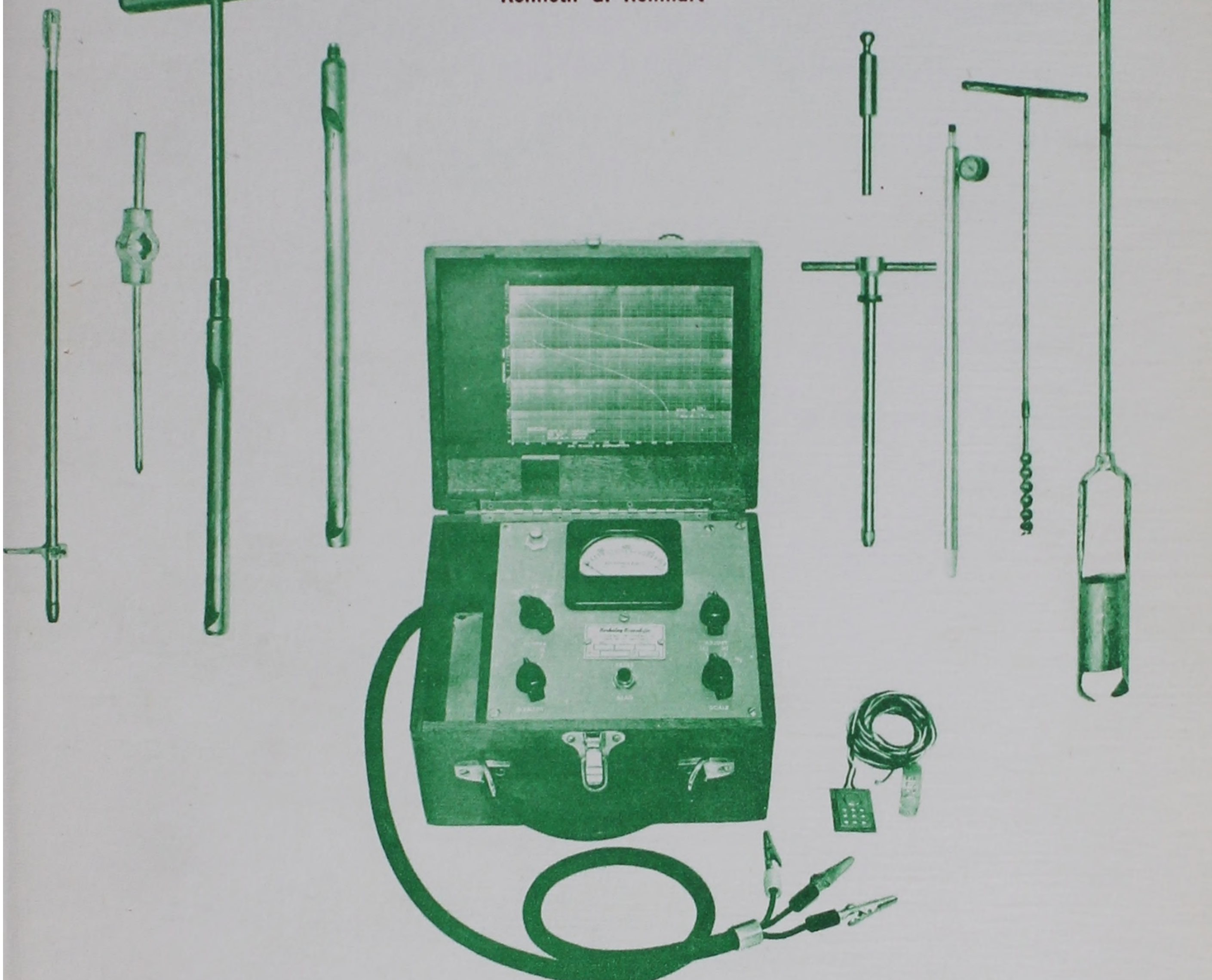

SOUTHERN FOREST EXPERIMENT STATION
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Predicting Moisture in the Surface Foot of Soil

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est storm which, on the average, showed a positive accretion. Storms less than the minimum were not used in the derivation of regressions nor in making predictions.

DEPLETION RELATIONS

Depletion curves were derived from the inter-rain portions of the graph of daily soil moisture contents by 6-inch layers for each season. The depletion portions were traced on an overlay, the individual portions being superimposed on the same graph by matching similar moisture contents. A smooth curve was then drawn through the family. The derived curves were started at the field maximum. Three composite curves —summer, winter, and spring-fall (transition)—are needed for each layer. A typical composite curve and a set of seasonal depletion curves are illustrated in figure 3. These curves give the expected daily moisture contents for consecutive days with no rain.

Four transition dates, representing the beginning and ending of the summer and winter seasons, were demarcated from the changing slope on the graph of daily soil moisture content during depletion periods.

The seasonal changes of depletion curves depend upon changes in the weather and the development or dormancy of the vegetation. These seasons do not correspond with calendar seasons, but vary between sites with differences in latitude and elevation.

The methods developed by Thornthwaite (4) and Penman (2) also take seasonal changes into account. Thornthwaite's curves for potential evapo-transpiration show a plateau of fairly constant high rates in the summer, a trough at low rates in the winter, and relatively short periods of rapid change in the spring and autumn. Penman uses seasonal factors to adjust evaporation from pans to evaporation from vegetated areas. His factors are 0.8 for 4 summer months, 0.6 for 4 winter months, and 0.7 for the 2 spring and 2 autumn months.

Within a season, the curves do not appreciably reflect daily changes in meteorological factors, which are small in comparison with the seasonal changes. In the surface foot, the soil and the moisture level apparently limit the loss of water. When the entire root zone is considered, however, meteorological factors within seasons may show more of a relationship to daily moisture losses.

Many curves show drainage losses at high moisture contents, particularly in winter, when such losses can be discerned for several weeks. In summer, high rates of evapo-transpiration can mask drainage losses. The central part of the depletion curve does not always have a constant slope; this part may still be influenced by drainage.

EXAMPLE OF PREDICTION METHOD

To make an estimate or prediction of soil moisture content for any given time, known or estimated starting soil moisture contents and precipitation by calendar days are needed. In addition, the field maximum moisture content, accretion and depletion relations, transition dates, and minimum storm size must be known. The starting moisture contents used may be the most recent occurrence of either field maximum or wilting point, as estimated by inspection of weather records.

Table 1-a is a prediction made during the period

Table 1-a.—Sample prediction of soil moisture content for Commerce silty clay site with herbaceous cover.*

April 1952	Moisture content		May 1952	Moisture content	
	0- to 6-inch depth	6- to 12-inch depth		0– to 6-inch depth	6- to 12-inch depth
	inches	inches		inches	inches
15	2.26†	2.68†	1	1.85	2.42
16	2.18	2.65	2	1.80	2.37
17	2.08	2.62	3	2.20	2.60
18	1.99	2.58	4	2.10	2.56
19	1.91	2.54	5	2.01	2.52
20	1.85	2.50	6	1.93	2.48
21	1.93	2.51	7	1.87	2.44
22	1.95	2.52	8	1.82	2.40
23	2.52	2.72	9	1.78	2.35
24	2.41	2.68	10‡	1.72	2.30
25	2.33	2.65	11	1.81	2.32
26	2.25	2.62	12	1.76	2.27
27	2.16	2.58	13	1.70	2.22
28	2.06	2.54	14	1.64	2.16
29	1.98	2.50	15	1.61	2.10
30	1.91	2.46			

*Field maximum moisture contents are 2.71 inches for the 0- to 6-inch layer and 2.85 inches for the 6- to 12-inch layer.
†Field sample values, to start the prediction.
‡Beginning of summer season.

April 15 to May 15, 1952, for a herbaceous site in Commerce silty clay. It illustrates: Class I and Class II accretions, a storm of less than the minimum size of 0.10 inch, several depletion periods, and a change of season. The prediction is based on relations derived from the previous year's data at this site.

The prediction begins in the spring transition period with actual moisture contents of 2.26 inches for the 0- to 6-inch layer and 2.68 inches for the 6- to 12-inch layer. For each succeeding day with no storm, the predicted moisture content for each layer is read from the transition depletion curves shown in figure 3.

The first storm of the period, a 0.19-inch rain, occurred on April 20. Predicted moisture contents of 1.85 and 2.50 inches for April 20 before the storm, are subtracted from field maximum moisture contents of 2.71 and 2.85 inches to determine available storage (0.86 inches and 0.35 inches in the 2 layers, as shown in table 1-b). Since total available storage of 1.21 inches is greater than rainfall of 0.19 inches, the accretion from the storm is Class I. For this soil, Class I accretions at 0.19 inches of rain are: 0.08 inches for the upper layer and 0.01 inches for the lower layer (as determined from the regression lines in figure 2). These are added to the predicted moisture contents of April

Table 1-b.—Prediction of accretion amounts for use in table 1-a.

Date	Amount of rain	Available storage		Accretion class	Accretion	
		0- to 6-in. depth	6- to 12-in. depth		0- to 6-in. depth	6- to 12-in. depth
April	inches	inches	inches		inches	inches
20	0.19	0.86	0.35	I	0.08	0.01
21	0.12	0.78	0.34	I	0.02	0.01
22	1.21	0.76	0.33	II	0.57	0.20
May						
2	0.89	0.91	0.48	I	0.40	0.23
9	0.05*	—	—	—	—	—
10	0.22	0.99	0.55	I	0.09	0.02

*Below minimum storm size.

20 (before the rain) to give predicted moisture contents of 1.93 and 2.51 inches for April 21 (after the rain).

The accretion from the April 21 storm is Class I. The April 22 storm yields an accretion of Class II because total available storage of 1.09 inches is less than rainfall of 1.21 inches. Accretion values of 0.57 inches and 0.20 inches for the 0- to 6-inch and 6- to 12-inch layers, respectively, were determined from the proper regression lines. The accretion values are added to predicted values of April 22 to obtain predicted values for April 23.

The predicted moisture contents for inter-rain periods are read from the transition depletion curve for each succeeding day until May 10, after which the summer depletion curve is used. The storms of May 2 and 10 are in Class I. The 0.05-inch storm of May 9 is less than the minimum storm size and is ignored, depletion being predicted as though no rain had occurred.

The deviations of daily predicted moisture contents from daily actual moisture contents are shown in table 2. A moisture content of 1% by weight is equivalent to 0.09 inches of water per 6 inches of soil in the Commerce silty clay.

Table 2.—Deviations of predicted from actual moisture content.

April 1952	Moisture content		May 1952	Moisture content	
	0- to 6-inch depth	6- to 12-inch depth		0- to 6-inch depth	6- to 12-inch depth
	inches	inches		inches	inches
15 (starting date)			1	−0.02	−0.08
16	0.00	0.00	2	+0.02	−0.07
17	−0.03	0.00	3	−0.08	−0.12
18	−0.04	+0.01	4	−0.10	−0.04
19	0.00	+0.01	5	−0.11	−0.03
20	+0.01	0.00	6	−0.08	−0.02
21	+0.09	+0.03	7	+0.06	−0.01
22	+0.06	+0.07	8	+0.01	0.00
23	+0.09	−0.02	9	+0.01	0.00
24	−0.04	−0.06	10	−0.06	+0.03
25	−0.08	−0.07	11	+0.06	+0.09
26	−0.08	−0.08	12	−0.05	+0.05
27	−0.05	−0.08	13	−0.10	+0.02
28	−0.08	−0.08	14	−0.11	0.00
29	−0.08	−0.08	15	−0.14	−0.02
30	−0.04	−0.09			

Future Application of the Method

The prediction method has given acceptable results when applied to the specific experimental sites from which the data were obtained. At present the accretion and depletion relations of all sites are being analyzed in order to systematize the method for general application. Vegetation, soil characteristics, topographic features, and climatic factors are being studied to determine their effect upon prediction relations. The object is to predict moisture for sites where only general knowledge is available and where it is impractical to secure soil moisture samples. A preliminary set of relations has been developed for such use and predictions from these relations are currently being checked against periodic samples at over 600 locations in the United States, Alaska, and Puerto Rico.

Studies are also under way to determine strength and moisture relationships for various soil conditions, with the ultimate purpose of forecasting trafficability for a wide variety of sites. At present, the method applies to military trafficability, but the results may prove useful in logging, construction, and other operations where heavy equipment must move off the roads.

The studies are also contributing to a better understanding of moisture conditions in the soil. Inasmuch as moisture gains and losses were not considered throughout the entire root zone, the present prediction methods cannot be used directly in irrigation or watershed management. However, they may be adapted to watershed studies where it is not feasible to measure soil moisture intensively.

Literature Cited

1. Carlson, Charles A., and Pierce, R. S. The field maximum moisture content. Soil Sci. Soc. Amer. Proc. 19:81–83 (1955).
2. Penman, H. T. The water balance of the Stour catchment area. Jour. Inst. Water Eng. 4:458–469 (1950).
3. Reinhart, K. G. Installation and field calibration of fiberglas soil-moisture units. U. S. Forest Service, South. Forest Exp. Sta. Occas. Paper 128, pp. 40–48, New Orleans (1953).
4. Thornthwaite, C. W. An approach toward a rational classification of climate. Geog. Rev. 38:55–94 (1948).

SOIL-MOISTURE MEASUREMENT

Howard W. Lull and Kenneth G. Reinhart

In agriculture, forestry, and engineering, considerable attention is devoted to the amount of moisture in the soil and its influence on such factors as crop yields, forest growth, and soil strength. Soil-moisture records are not easily secured. By conventional methods, soil sampling is laborious, and drying of samples is time-consuming. Sampling results are often exceedingly variable, for soil moisture changes from day to day, point to point, and depth to depth. Certainly, it is as difficult a factor to measure as any encountered in hydrologic research.

Because of the importance of soil-moisture records and difficulties in securing them, considerable time and energy has been spent in developing new ways of measuring moisture. This paper reviews most of these methods, describes and compares the most commonly used instruments, and discusses soil-moisture expression, variation, and sampling. Wherever possible the authors have relied on first-hand experience gained at the Vicksburg Infiltration Project. 1/

Development of Methods

Current methods of estimating soil-moisture content range from the age-old one of feeling the soil to the recent employment of radioactive materials and associated intricate and expensive instrumentation. In the pages immediately following, the various methods are briefly reviewed in rough chronological order. Later sections will describe in detail the three now in common use--gravimetric, electrical resistance, and tensiometer--and will summarize experience so far with nuclear instruments.

1/ A cooperative soil-moisture study conducted by the Southern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, for the Waterways Experiment Station, Corps of Engineers, U.S. Army. Project headquarters are at Vicksburg, Mississippi.

Consistency Tests

Since ancient times, estimates of soil consistency have been used to judge the best times for plowing and cultivating and the amount of moisture available for plant growth. An early recorded observation has been cited by Keen from Fitzherbert's Boke of Husbandry, published in 1523: to find out if the soil was ready to be sown to peas and beans, the husbandman was directed to walk on the plowed land "and if it synge or crye, or make any noise under thy fete, then it is to wete to sowe: and if it make no noyse, and wyll beare thy horses, thanne sowe in the name of god" (43). 2/

Farmers still pick up and squeeze a handful of soil before working their fields. Such simple moisture estimates can be very accurate. In 1937, Stoeckeler reported that forest nursery personnel had been trained to gage the total moisture content of the soil within 2 percent (78). More recently, Diebold has described a series of manual strength tests for estimating readily available moisture in medium- to fine-textured soils (32).

Gravimetric Method

One can only guess when the first soil-moisture measurements were made--perhaps in the eighteenth century. Russell gives results of soil-moisture studies started at Rothamsted in 1843 (68). One of the illustrations in a recent edition of his text compares moisture under cropped soil and under a fallow area after a prolonged drought in 1870. Whenever made, the first measurement probably consisted of weighing a sample before and after drying--essentially, the gravimetric method.

This was the method used by the Department of Agriculture when it started about 1894 to study "the circulation of water in some of the important types of soil in the United States" (88). Samples were taken to a depth of 12 inches with a 15-inch brazed brass tube 7/8-inch in diameter. After both ends of the tube had been sealed with rubber caps, the 75- to 100-gram sample was carried to the laboratory and dried at 110°C. for 20 hours. Moisture content was expressed, contrary to present-day practice, in percent by weight of the original moist sample (89).

2/ Underscored numbers in parentheses refer to Literature Cited, p. 47.

Dr. F. J. Veihmeyer states in correspondence that the idea of using a tube for sampling soil is old, antedating the development of the well-known King tube in 1890. He also notes that by 1897 the Department of Agriculture was reporting soil moisture on a dry-weight basis, as is done today, and that as early as 1892 Hilgard, in a report of the California Agricultural Experiment Station, gave moisture determinations with respect to both weight and volume.

Since these early beginnings, efficient types of drying ovens, scales, and sampling instruments have been developed. The gravimetric method is still the most widely used technique for obtaining soil-moisture records. Moreover, as the only direct way of measuring soil moisture, it is indispensable for calibrating instruments used in the indirect methods.

The gravimetric method has several serious disadvantages. Much labor is required to secure the samples and considerable time is needed for drying them. Repeated sampling destroys the experimental area. Evaluation of moisture differences between successive samples is complicated by the fact that no two samples can be taken from exactly the same point. The elimination of these disadvantages has been the goal of many investigators.

Soil Points

From about 1920 to the present, researchers have studied the possibility of estimating soil moisture from changes in the weight of porous blocks or points placed in the soil. Livingston and Koketsu, who developed the original blocks, found that permanent wilting began when a block failed to absorb more than 85 milligrams of water after two-hour exposures in soils of various textures (47). Wilson noted that plants remained healthy as long as there was about 500 milligrams' increase in weight of a point set at a soil depth of 6 centimeters for one hour; the critical value for beginning of drought was about 100 milligrams (91). Stoeckeler found that specific gains in weight of soil points could be used to indicate the moisture condition of a light sandy loam (78). Davis and Slater have described a soil point made up of a porous chamber within which is a close-fitting plug that can be removed for weighing (29). Recently, Dimbleby has developed a porous clay pencil which is stuck into the soil. Comparative moisture contents are estimated after one hour from the color change as moisture moves up the pencil (33).

Water-Absorbing Liquids

The techniques using water-absorbing liquids and the several other "rapid" methods were developed mainly to avoid the 24-hour

oven-drying period that is more or less standard in the gravimetric sampling method. Some of these methods show promise, but they frequently require more of the investigator's time than do weighing procedures associated with oven-drying.

In 1936, Begemann described a method of determining soil-moisture content by adding xylol to a sample, distilling off the xylol and water, and measuring volumetrically the distilled water (4). The process takes about 45 minutes. In several comparisons, variation from oven-drying ranged from 0 to 0.4 percent. Bidwell and Sterling reported a similar method in which toluene was used as the immiscible liquid (8). The time required for the individual moisture determinations is the obvious limitation of this method.

In 1927-1931 Bouyoucos described the alcohol method, the first of several methods developed by him. The procedure consisted of mechanically dispersing a 25-gram soil sample in 75 milliliters of pure methyl alcohol, filtering the solution, and determining its specific gravity with a special alcohol hydrometer (9). Moisture content was determined by calibrating the hydrometer in known mixtures of alcohol and water. The method was accurate, but Smith and Flint (74) noted that it required 3 to 5 times as much operator's time as is needed in oven-drying.

Heat of Solution

This method utilizes the principle that a mixture of water and concentrated sulphuric acid produces heat in proportion to the quantities mixed. Emmert employed it by using 2 milliliters of acid and 1-gram portions of soil, and measuring the rise in temperature of the solution (35). Separate calibration curves have to be derived for each soil type. The method is reported accurate to about 0.5 percent by weight. Extreme care must be exercised in using the correct volume of acid and correct weight of soil.

Heat Diffusion

The rate of transmission of heat through soil varies with soil-moisture content. For dry soils the heat conductivity is low because the particles make only point contact. As water is added, the area for conduction is greatly increased, and the temperature differential around a heat source is consequently reduced.

Recently, more than 50 moisture cells employing this principle were tested (1). Changes in soil temperature were determined by a thermistor attached to a current-measuring circuit. None of the cells

measured the full range of moisture content. If a successful cell is developed, it will require separate calibration for different soils and densities.

Shaw and Baver noted that heat conductivity-moisture content relationships for clay and sand samples gave entirely different curves that reflected differences in pore space distribution (71). They also found that concentrations of salt ranging from 100 to 10,000 parts per million had no effect on the readings.

Momim measured heat diffusion with a thermometer inserted to a soil depth of two feet (50). He passed a fixed current through a heating element wound on the bulb and recorded the time required to raise the temperature 5°C. This device was field-calibrated.

Calcium Carbide Method

In 1940, White-Stevens and Jacob described an interesting method based upon the reaction of calcium carbide with free water (87). Ten grams of soil are placed in a specially designed container with an equal weight of calcium carbide. When the container is shaken, the soil moisture comes in contact with the carbide and gas is formed. The moisture content is calculated from the equivalence that each 26-gram loss in weight represents 36 grams of water.

Constant-Volume Methods

Papadakis, in 1941, suggested a method based on addition of water to soil samples to make up a constant volume (57). The difference between the weight of the soil-water volume and the weight of an equal volume of water, when multiplied by a factor, gives the oven-dry weight of the soil. The factor has to be determined for each kind of soil by dividing the oven-dry weight (obtained conventionally) of one sample by the difference mentioned above. Fifty-gram soil samples were used and water was added to make 100 milliliters.

For soils that do not vary widely in volume weight, Uhland (81) has suggested the possibility of determining moisture content very quickly by weighing a given volume of undisturbed soil and comparing it to an average oven-dry weight of the same volume.

Resistance to Penetration

Moisture content can be estimated by relating it to the force required to push an instrument, often called a penetrometer, through

the soil. An example is the device developed by Allyn and Work to measure the amount of force required to drive a pair of needles into a soil core (3). For soils in which the instrument had been calibrated, total moisture content could be estimated within 0.5 percent, or within 2 percent of the available moisture capacity. A similar error of estimation was obtained with an instrument later developed by Allyn (2). This instrument measures the resistance offered to rotation of a diamond-shaped steel point driven into the soil.

With any penetrometer, considerable difficulty is experienced in stony soils.

Electrical-Resistance Method

The use of soil points and the heat-diffusion method were attempts to measure moisture *in situ* in order to preserve the sampling point and thus provide continuity in both space and time to soil-moisture records. This is not possible in gravimetric sampling, where a moisture difference in successive samplings may be due either to an actual moisture change with time or to variation in moisture content between sampling points.

The most successful of the *in situ* devices have been the electrical-resistance instruments which operate on the principle that resistance to the passage of an electrical current between 2 electrodes buried in the soil will depend on the moisture content of the soil. This idea is not new; the Department of Agriculture used it from 1896 to 1899 (90). Results were unpromising, largely because of the variability in contact between the electrodes and the surrounding soil particles.

The first successful device appeared in 1940, when Bouyoucos and Mick embedded the electrodes in a plaster of paris block (17). Six years later a fiberglas unit was described by Colman (26). In 1949 Bouyoucos brought out a fabric unit made of nylon (11).

The use of fabric or plaster of paris permits uniform electrode contact with moisture, and thus overcomes the major failing of earlier instruments. Buried in the soil, the porous material of the unit wets and dries along with the soil around it, and the changes in moisture content affect the electrical conductivity or resistance of the unit. Wires lead from the unit to the surface of the ground, where resistance is read with a meter. To convert resistances to soil-moisture values requires calibration of the units in the soil being studied.

Tensiometers

Tensiometers came into prominence about the same time that electrical-resistance units were developed, Richards presenting a definitive paper on them in 1942 (61). Tensiometers measure soil moisture tension at high moisture contents. Essentially they consist of a porous ceramic cup connected to a vacuum gage or mercury manometer. When the system is filled with water, the water in the cup comes into equilibrium with that in the surrounding soil. As the soil dries or wets, water flows from or into the cup: these changes activate the pressure-measuring device. The instruments function to a tension of 0.8 to 0.9 atmosphere. At greater pressures, air enters the system.

Air-Picnometer

With the air-picnometer developed by Russell, soil moisture, as well as bulk density and percentage of air-filled pores, can be measured directly in the field (67). The method consists of taking a soil core and placing it in an air-tight system at barometric pressure. The volume of the system is then changed a known amount and the resultant pressure measured. This value is used with data on the total volume of the system, the volume change, and volume of sample to calculate the percentage of the sample volume that is filled with air. Moisture content can then be computed from the weight of the sample and an estimated specific gravity of 2.6. At the Vicksburg Project these calculations are made through a series of nomographs. According to Russell's data, most deviations of actual from estimated soil-moisture values were less than 2 percent.

This method is not recommended for soils containing over 5 percent organic matter or for stony soils, since the estimated specific gravity cannot be applied. Broadfoot recently developed a convenient sampler for taking cores that fit the air-picnometer (19).

Nuclear Method

In 1950 a method based on use of radioactive material was introduced (5). The technique involves measuring the slowing down of neutrons emitted into the soil, an effect proportional to the concentration of hydrogen atoms. Still in the developmental stage, this new method holds considerable promise.

Summary

Of the 13 methods that have been described, only the gravimetric, electrical-resistance, and tensiometer methods are commonly used. Consistency tests and penetrometers are useful for approximations but will not give the accuracy required for most records. Soil points provide only relative measurements. The heat-diffusion method awaits usable instrumentation. The air-picnometer possesses the advantage of speed but at the cost of accuracy. The other methods--water-absorbing liquids, heat of combustion, calcium carbide, and constant volume--have little promise because they take too much time or are inaccurate. The nuclear method requires further development. The commonly used methods also have their disadvantages. In short, a method that will give accurate, rapid, *in situ* values has not yet been perfected.

Gravimetric Method

As has been noted, the gravimetric method is the only commonly used direct means of measuring soil moisture. Simply, it involves taking a soil sample, weighing it, oven-drying it, reweighing, and expressing the original moisture content in percent of oven-dry weight of soil. The first step, securing the sample, is the most troublesome, the degree of difficulty depending on the condition of the soil.

Soil-Sampling Conditions

Sampling conditions are ideal when soil is just moist enough for easy ingress and egress of the sampling instrument, and where stones, roots, and organic matter are not a problem. Such conditions are seldom encountered.

With free water in the soil, moisture can never be sampled accurately: water will drip off as the sample is removed from the ground or compaction may squeeze it out. Rapid sampling is essential to prevent undue losses. Stickiness, often a problem in wet soils, can be alleviated by keeping instruments clean.

Where a wet layer overlies a dry one, samples taken from the drier levels may be contaminated. After the upper soil is wetted by a summer rain, for instance, removal of a sample may permit water to run down the hole toward drier soil. The same problem is encountered when samples are taken below a perched water table. Wet instruments add to contamination and should be dried between samplings.

When the soil is dry and hard, the principal problem in fine-textured soils is to get the sampling instrument in and out again. In coarse-textured soils particularly, samples may slide out of the instrument as it is withdrawn from the soil. Fortunately, after the soil dries in summer, its moisture content may fluctuate so little that frequent sampling may be unnecessary.

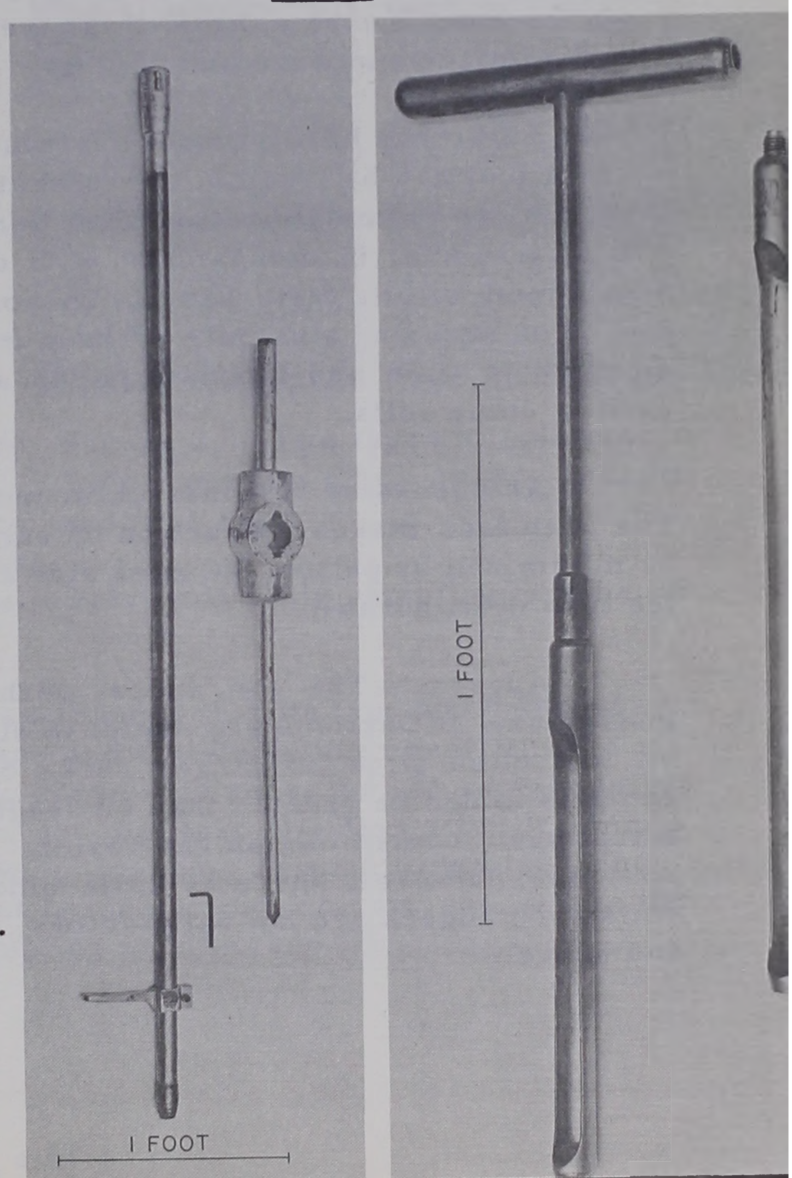
In certain sections of the country, the problem of stoniness outweighs all others. Stones of any size make it difficult to secure samples and to express moisture content in a useful way. Generally speaking, larger soil samples are required in stony areas and moisture content should be expressed in terms of both the total sample (stones included) and of only the material below the size of coarse sand. In forest soils, heavy accumulations of organic matter and large roots often make sampling difficult.

Instruments

The type of sampling instrument to be used is determined largely by the soil conditions most likely to be encountered. All of the instruments are designed so that an equal volume of soil will be taken per unit increase of depth.

Soil tubes.--The most commonly used sampler is the soil tube, often called a King tube or Veihmeyer tube. Essentially, it is a pipe of about 1-inch diameter which can be obtained in lengths from 3 to 20 feet (fig. 1). As modified and improved by Veihmeyer (84), this tube cuts into mineral soil with a minimum of compaction, though wet clay samples more than a few inches in depth and samples high in organic content tend to compress within the tube.

Figure 1.--Two types of soil tubes. Left, soil tube and hammer; the step facilitates sampling of uniform shallow depths. Right, open-side tube.



The tube is driven into the ground with a hammer weighing about 15 pounds. A specially designed jack is often necessary to retrieve tubes driven more than 2 feet into dry soil.

To help prevent the core from falling out when the sample is withdrawn from the soil, the lower end of the tube is somewhat constricted. Loss of dry sandy samples can often be prevented by lightly compacting the soil in the tube with a rod (84). In very wet clays, loss of core by suction can be avoided by closing the open end of the tube, while withdrawing it, with a rubber stopper or the palm of the hand. Tubes may be provided with a variety of points for sampling soils of different textures.

When sampling is especially laborious or when sharp moisture gradients may lead to contamination of samples, a core to the total depth of sampling may be taken and apportioned as necessary. The division of the entire core into successive increments is facilitated by using an inclined measuring trough (37). Under normal sampling conditions, however, samples of the successive layers should be drawn from the hole one at a time; this gives better control of sample depth and minimizes exposure and drying.

Soil tubes have several advantages. A sample from a depth of several feet can be taken in one operation; as the soil is enclosed, it is less subject to contamination than samples taken by augers or open-side tubes; and, in comparison with other instruments, tubes cause a minimum of site disturbance. In some dry soils, tubes are the only means of securing a sample. Their main disadvantages are the large amounts of time and labor required and the fact that they cannot be used in stony soils.

An open-side tube useful in moist soils is shown in figure 1. The open face makes extraction of samples easy. Contamination may be minimized by pulling the open side away from the wall of the hole as the tube is withdrawn.

Augers.--The soil auger, perhaps the most familiar sampling instrument, is particularly useful in sticky or in stony soils (where the bit will often slide off larger rocks on its downward course). Since samples to depths greater than bit length can be taken only by successive samplings, contamination can result. When the soil is too stony for a soil-tube, however, there is little other choice. In some dry, stony soils even augers are not satisfactory, and the only recourse is to pick and shovel.

Two augers are shown in figure 2. According to the Soil Survey Manual (76), the screw auger consists of a 1-1/4 or 1-1/2-inch wood bit, with cutting lips and tip removed, welded to a steel rod with a handle. The worm should be about 7 inches long with distance between flanges about the same as the auger's diameter.

The Iwan or posthole type is particularly useful in gravelly soils or when sizeable samples are desired. The sampler pictured has an inside diameter of 4 inches and a barrel length of 8 inches. Smaller augers are available. As the auger is rotated, the cutting blades loosen the soil and force it into the cylinder. Under favorable conditions, and with shaft extensions of common pipe, this auger can be used to sample to depths of 20 feet or more.

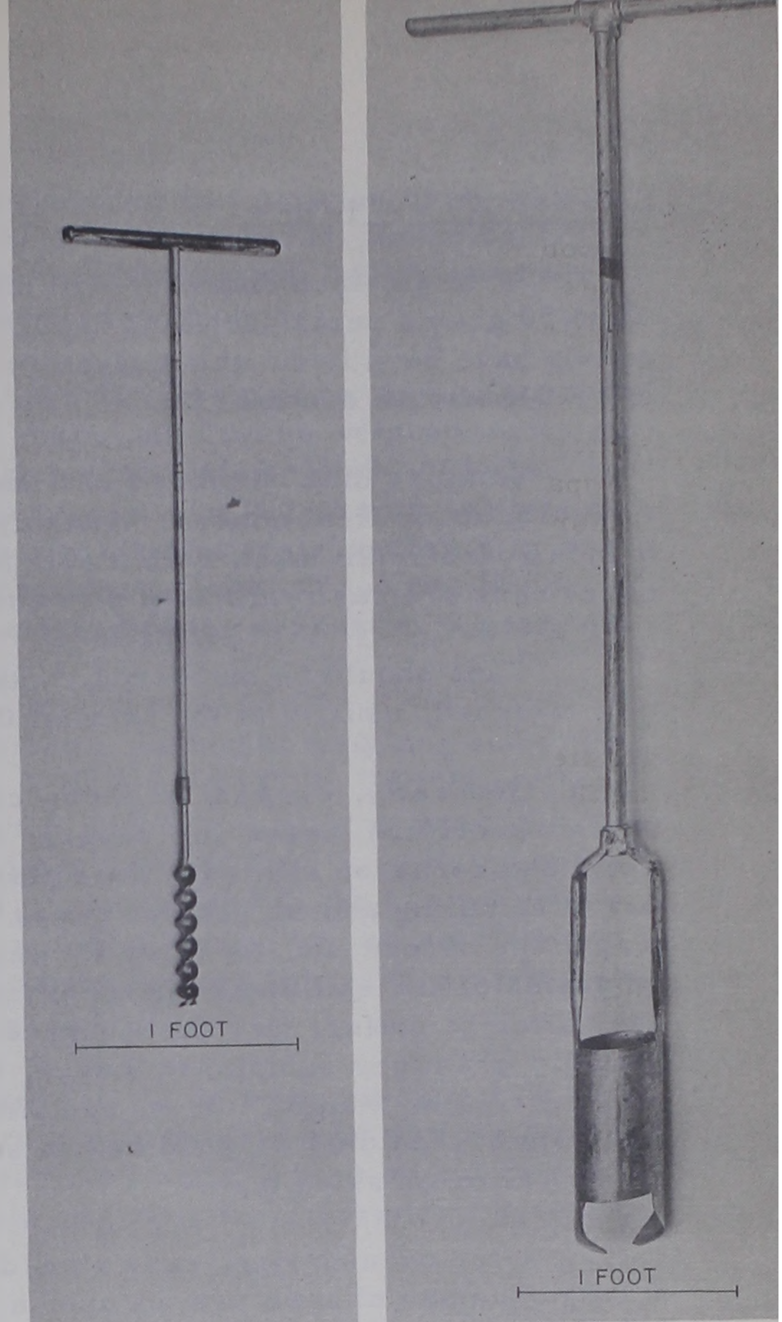


Figure 2. --Two types of soil augers. Left, common type. Right, Iwan or posthole type.

Depth and Frequency of Sampling

The depths sampled depend on the objectives of the study. If the intent is to determine moisture supplies for plant growth, sampling should include all of the root zone. Relatively little sampling is done below 5 or 6 feet.

Gravimetric sampling is so arduous that its frequency should be directed by close regard to weather and soil-moisture conditions. For instance, to define the soil drying curve it is necessary to sample daily, or perhaps even more frequently, for the first few days after irrigation or after soaking rains in the growing season. At such times, the rate of change in soil-moisture content is most rapid. As the soil dries, the rate of change decreases and sampling may be less frequent.

Soil-Sample Containers

With a 1-inch diameter soil tube, samples generally run from 25 to 50 grams per 3-inch soil depth. Samples weighing less than 10 grams have been found unsatisfactory for the accurate determination of soil-moisture content (52).

Samples may be placed in tinned cans having capacities of 3, 4, 8, 16, or 32 fluid ounces. Roughly, the 4-ounce can holds a 3- to 6-inch soil sample taken with a soil tube or screw auger. Boxes to carry cans are easily made of plywood (37).

Cans should be numbered, both on the lids and the sides, and tare-weighed, usually to the nearest 0.1 gram.

Generally, the seal on these cans is considered sufficient to prevent moisture losses for several days. In a recent test, 6-inch soil-tube cores of silt loam were placed in cans and weighed on the day of sampling and at various times thereafter to determine the magnitude of loss due to delay in weighing. The samples averaged 60 grams of dry soil and 30 percent moisture by weight. In the first 2 days after sampling, no loss occurred. In 3 days; loss averaged less than 0.1 gram per sample; in 9 days, 0.2 gram; in 29 days, 0.6 gram or 1 percent by weight. When samples are stored for long periods, they either should be weighed before storage or sealed in the cans with electrical or masking tape.

After oven-drying, cans should be thoroughly cleaned. Where a large number of cans are in use, a motor-driven bristle brush is helpful. Tin cans in frequent use often do not last more than a year. An acid- and heat-resistant varnish delays rusting but may make the cans more difficult to open. Aluminum cans may be used but they are expensive and dent easily--after which lids will not fit tightly.

Because of convenient packaging, air-tightness, freedom from rust, and ease of procurement, 1/2-pint Mason jars have been used on the Vicksburg Project to hold 18-inch soil-tube samples.

Oven-Drying and Weighing

As a common practice, samples are oven-dried at 105 to 110° C. to a constant weight. A 24-hour period is generally used. If large numbers of samples are to be dried, forced-draft ovens are desirable; they can dry 50-gram samples in 4 to 6 hours.

Davisson and Sivaslian recommended that soils be dried in an electric oven at 105° C. in a vacuum over phosphorus pentoxide (30). With this procedure 4 hours' drying was sufficient. Slightly more moisture was removed than with standard oven-drying.

Generally, samples of less than 100 grams are weighed to the nearest tenth of a gram. When many are to be weighed daily, a rapid-reading laboratory scale, such as the Toledo Model 4636BA, is worth the investment. With samples larger than 100 grams, allowable error may permit use of an inexpensive dietetic scale accurate to one gram. To speed up weighing on a torsion balance, Olson and Hoover (51) suggest that samples first be weighed to the nearest 0.5 gram on a direct-weighing scale.

Stout and Holben have described a method of weighing and drying that will give moisture content in 2 to 3 hours (79). In this method, 20-gram soil samples are placed in 4-ounce soil cans of exactly equal tare weight and dried in a forced-draft oven at 130° C. After drying, the samples are weighed on a scale counterpoised to the can weight so that the difference between the dry weight and 20 represents the moisture loss. According to the authors, results checked closely with those obtained by drying overnight at 105° C.

Sen (70) dried 10- to 15-gram soil samples by placing them in a fused silica basin held 2 to 3 inches above the flame of a rose Bunsen burner. The soil, which was stirred constantly, dried completely in 3 to 6 minutes. Moisture contents did not vary from oven-dry values by more than one percent.

Bouyoucos (10) has suggested treating soil samples with alcohol and burning off the alcohol to remove the water. Carter (23) found that it required about five minutes to make a determination in this way and that the moisture percentages obtained were slightly higher than those determined by oven-drying. Considering the time required, he believed the method worth while only for field determinations.

Electrical-Resistance Units

The development of electrical methods has been excellently summarized by Olson and Hoover (53). Herein major emphasis will be placed on the most common instruments and their use. Much of this material is a condensation of earlier papers prepared at the Vicksburg Project (55, 59).

Types of Instruments

Currently, three types of units are in use: the fiberglas unit developed by Colman and Hendrix (27), the nylon unit developed by Bouyoucos (11), and the plaster of paris or gypsum block of Bouyoucos and Mick (17). These three units are shown in figure 3, together with a fiberglas-gypsum unit that was developed by Youker and Dreibelbis (93) but has not come into general use.

Dimensions and details will be found in table 1. In the fiberglas unit, electrical resistance is measured between two monel metal screens separated by two layers of fiberglas cloth, the whole enclosed in three layers of the same material and bound in a monel metal case that is spot-welded at the edges. The fiberglas unit differs from all

Figure 3.--Soil-moisture units and meters.

Table 1. --Dimensions and details of electrical soil-moisture units

Item	Type of unit			
	Fiberglas	Nylon 1/	Plaster of paris 2/	Fiberglas-gypsum
Outside dimensions, inches	1.5 x 1.0 x 0.12	1.5 x 1.25 x 0.12	1.7 x 1.25 x 0.7	2.5 x 1.5 x 0.5
Absorbent material between electrodes	2 layers of fiberglas	1 layer of nylon	Plaster of paris	Fiberglas, plaster of paris
Distance between electrodes, inch	.03	.03	.19	.75
Electrodes:				
Area, square inch	.39	2.0	.46	...
Length, inch	...	...	...	.25 -.50
Mesh, wires per inch	60	96	20	...
Area of fabric in unit, square inches	5	5.6	...	...
Area of absorbent exposed to soil, square inches	.20	1.20	8.38	11.50

1/ This unit is now available encased in plaster of paris. The "nylon-plaster" unit has outside dimensions of 1.90 x 1.70 x .46 inches.

2/ Data for unit as now manufactured with wire-screen electrodes.

others in that it contains a thermistor, thus permitting soil-temperature measurements by which resistances may be corrected to a common temperature. The resistance between the electrodes is read with a battery-operated alternating-current ohmmeter.

The nylon unit, similar in shape and size to the fiberglas, consists of two electrodes of fine metal screen to which wire leads are silver-soldered. The electrodes are separated by wrappings of nylon and enclosed in a perforated nickel case with edges mechanically united. A later design has the case and electrodes of stainless steel (13). This unit differs from the fiberglas by having larger grids for electrodes and a much greater area of fabric exposed to the soil.

The plaster of paris block was first constructed simply by embedding two electrodes, each two inches long, in plaster of paris. As now manufactured, the block has electrodes of stainless steel screen (15) and is impregnated with a nylon plastic resin for greater durability (14). The fiberglas-gypsum block is similar to the plaster of paris,

but the two electrodes are separated from the plaster of paris by a layer of fiberglas cloth. Recently, Bouyoucos has encased his nylon unit in plaster of paris (16).

Resistances of units other than fiberglas are measured with a modified Wheatstone bridge developed originally for use with the plaster of paris block (18). They may also be determined with the ohmmeter used with the fiberglas unit.

Installation

Careful installation of units is extremely important (59). Units should be installed when the soil is moist enough to pack well; it should be below field capacity but not dry and hard. Unless the excavated soil is repacked to at least its original density, an artificial channel may be created through which water will travel rapidly to the units. Such a channel is indicated when, after a rain, soil samples at a given depth are still dry whereas the resistance of the corresponding unit has dropped significantly. The problem is especially serious when the natural soil has a hardpan or other layer of low permeability that is difficult to duplicate when refilling excavations.

At the Vicksburg Infiltration Project, fiberglas units were first installed in pits. Since this involved considerable soil disturbance and was time-consuming, further installations were in 5-inch auger holes. Units are pressed into the sidewall of the hole; to avoid disturbance between units, unit positions were 45 degrees apart (fig. 4). At first, a stick with a notch cut to fit the unit was used to press the unit into the wall of the hole; later a device for mechanically inserting the unit was devised (54).

The units are placed in the soil perpendicular to the ground surface. To prevent water movement along the wires to the units, the wires are led slightly downward before being brought to the surface. Soil is replaced in its original position and repacked to at least its original density. Under favorable soil conditions three stacks of ten units each,

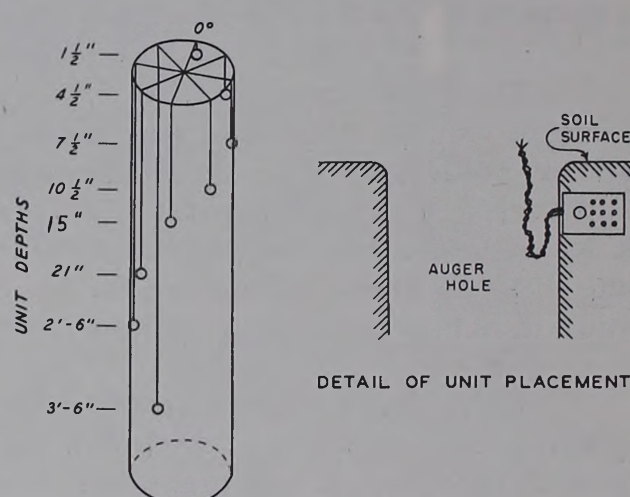


Figure 4.--Installation of fiberglas units in auger holes.

with the deepest unit at 42 inches, have been installed in two man-days. With recently developed equipment for insertion of plaster of paris blocks, 7 units were installed in 15 minutes (49).

To facilitate reading, lead wires from the units can be wired into several different types of terminal panels or switch housings (34, 56, 92). A simple terminal panel (fig. 5) for fiberglas units can be made of 1/2-inch Plexiglas, 2-3/4 inches wide and long enough to accommodate the number of terminals desired. Lead wires from the units are soldered to brass bolts inserted in the Plexiglas.

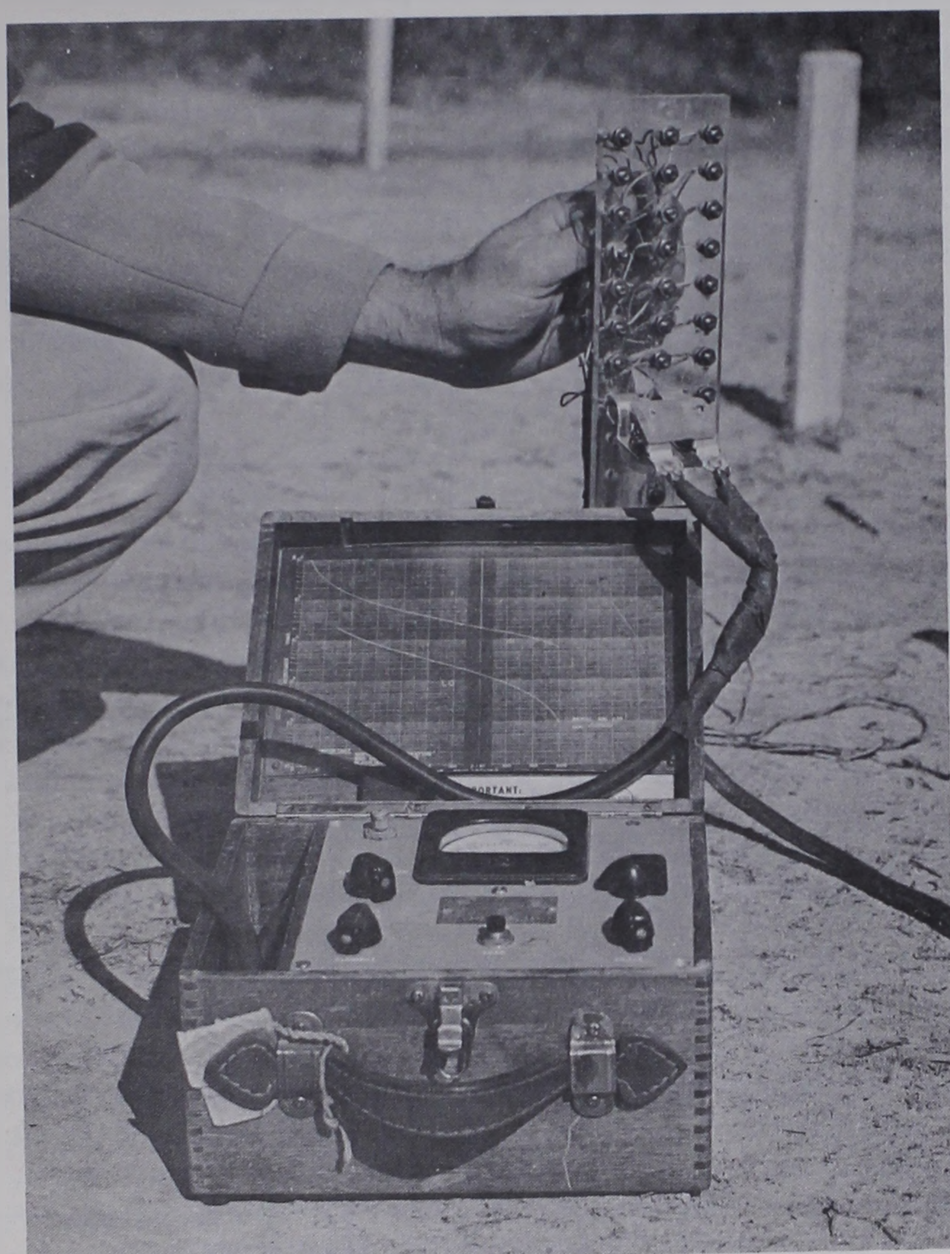


Figure 5. --Terminal panel.

In field calibration each stack of units requires an adjacent soil-sampling area. Samples must be taken close enough to the unit to represent the same moisture condition, yet not close enough to disturb the natural soil and moisture relations at the unit. The area must be large enough to take care of repeated samplings.

Sampling areas used by the Vicksburg Project have varied. The arrangement in figure 7 has been found most satisfactory, primarily because it avoids disturbing the central plot containing the stack of units. Samples, usually in duplicate, are taken with a soil tube from square-foot blocks, one sample from each of two of the 6- by 6-foot plots. Plots and blocks are randomly selected.

Successive soil cores are removed from each sample hole. The mid-point of a core corresponds to the depth of the unit being calibrated, and the length of the core is generally made to equal the thickness of the layer represented by the unit. After sampling, holes are packed with similar soil to prevent movement of water to the lower depths.

When rain follows a dry period the depth of wetting may vary considerably between points only a few feet apart, and the moisture content at the unit may differ from that at either sampling point.

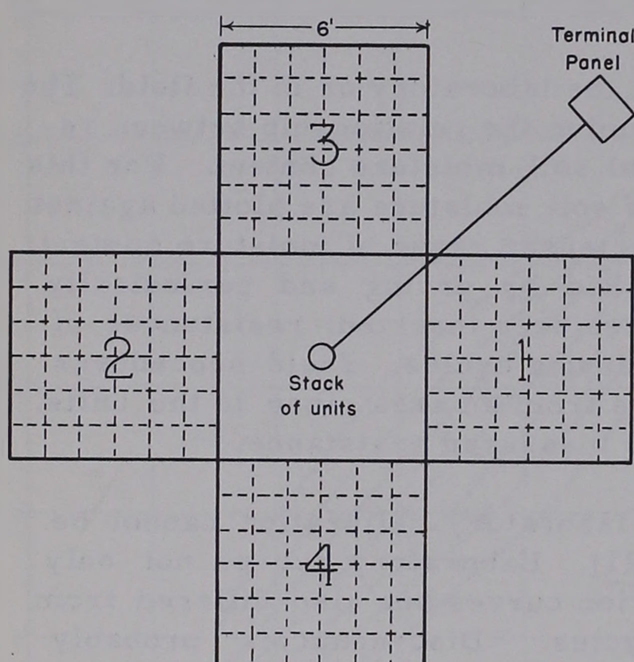


Figure 7.--Calibration plot arrangement.

After samples have been taken to establish the wet end of the curve, periodic sampling during drying periods of the growing season will provide for the remaining range of moisture content. Since the soil often dries rapidly, frequent sampling may be required to define the middle section of the curve. After calibration curves are drawn, occasional samples should be taken throughout the duration of a study as a check on continuing reliability.

Variation within the soil frequently causes a difference of several percent in moisture content between duplicate samples.

Inspection of the values for the soil layers just above and just below the values in question may give a clue as to whether the difference is due to error in measurement or truly represents soil conditions.

Calibration curves. --A calibration curve--an example of which is given in figure 8--is prepared for each soil-moisture unit. Each moisture-content value of the duplicate samples and the mean value is plotted from the abscissa against corresponding resistances measured on the ordinate. Resistances can be most conveniently plotted on a 4-cycle logarithmic scale, or, if the logarithm of resistance is used, on an arithmetic scale. On the average, 15 to 20 duplicate samples, taken at moisture contents ranging from saturation to wilting point, adequately define the calibration curve.

Points should be plotted as data are obtained. When sufficient points show reasonable agreement, the calibration curve is drawn. This calls for some judgment: for instance, individual samples of a pair that vary widely should be given less weight than pairs that agree closely. In general, all samples taken when the moisture content varies considerably from depth to depth are subject to doubt.

Conversion of Resistance to Moisture Content

After the development of the calibration curve, resistances, corrected to a common temperature, can be converted to moisture contents. Moisture contents may be read directly from the curve, or a table may be prepared from the curve. With plaster of paris blocks, a slide rule (66) may be used to correct the observed electrical resistance for soil temperature variations and to change the resistance readings to percentage of available moisture. On the Vicksburg Project, moisture content was marked on the abscissa of the calibration curve in both percent by weight and inches depth of water. Thus, after calibration

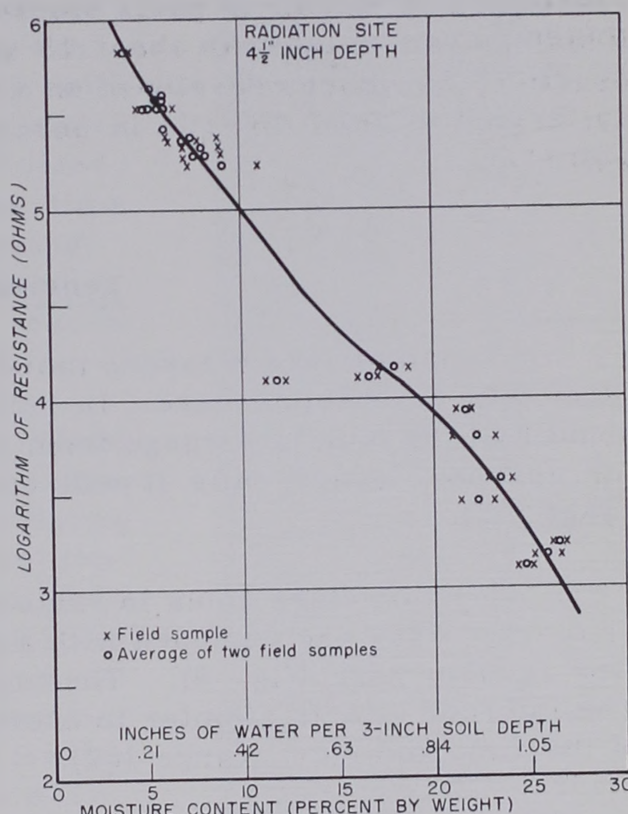


Figure 8. --Typical calibration curve.

data have been plotted in percent by weight, daily resistance values can be readily converted to inches depth for the soil-moisture record.

Recording Instrument

Resistance readings are usually taken daily or less frequently. For more frequent readings, Korty and Kohnke hooked a recording potentiometer, connected with an ohmmeter circuit, to nylon units (44). Readings were recorded at 8-minute intervals. Maximum accuracy was 5 to 10 percent of the resistance being measured--10 percent of the resistance was equal to a 1/2 percent error in soil-moisture content. This instrument responded to sudden changes in soil moisture from rainstorms and was useful in following general soil-moisture conditions. To measure small changes in moisture, more costly devices are necessary.

Other Types of Meters

Since the development of the modified Wheatstone bridge, more simple types of instruments have been devised for use with Bouyoucos units. One is a light-weight instrument that measures the electrical resistance of plaster of paris blocks to passage of a direct current (46). Readings can be taken in about 15 seconds. As a guide to irrigation practice, Bouyoucos developed an alternating-current impedance meter calibrated to read directly in percentage of available moisture in the soil (12).

Tensiometers

Tensiometers measure moisture content through a tension range from 0 to 0.85 atmosphere. In soils of the finest texture this covers about half the moisture range from field capacity to wilting percentage; for coarser, sandy soils it will cover more than 90 percent of the range (62).

Tensiometers come in various lengths from 6 inches to 4 feet or more. They are equipped with a mercury manometer or a Bourdon-type vacuum gage (fig. 9). The manometer type is more accurate. The Bourdon type is simpler to operate; it gives precision of 2 percent of the field moisture range (62).

Field installations have been made to depths of 15 feet (61). The instruments can be placed in soil-tube holes; soil around the top four inches of the hole is tamped to prevent runoff from flowing downward to the cup. According to Richards (61), two men in less than two

hours installed 36 instruments at depths from 6 inches to 5 feet. About 8 hours is required for the instrument to reach equilibrium. When first set out, the system should be filled with boiled distilled water. Thereafter, when only small amounts are added, the water need not be boiled. With freezing temperatures, instruments must be brought in from the field; however, a wool sock over the gage is sufficient protection for the Bourdon type at temperatures slightly below the freezing point.

Tensiometer readings are subject to daily variations. Haise and Kelly (38) found that in Yuma fine sand the variation extended to a depth of 48 inches. Daily variations in tension of 350 to 400 centimeters of water at the 6-inch depth were common. These variations are believed due to temperature gradients (between the porous cup and the surrounding soil) which affected vapor transfer and condensation. The effect can be minimized by reading tensiometers at the same time each day, preferably in the morning. Richards and Gardner used a recording vacuum gage to obtain a continuous record of tension (63).

To obtain moisture-content values with tensiometers, calibration is necessary either by taking field samples and relating their moisture content to concurrent tensions, placing a tensiometer in a container of soil that can be weighed from time to time to get moisture changes, or determining a moisture content-tension relation in the laboratory by using tension tables and pressure membrane cells. Scofield, working with the first two methods, secured best results with an open container of growing plants (69). The soil in the container was saturated and weights and tensions were recorded as it dried.

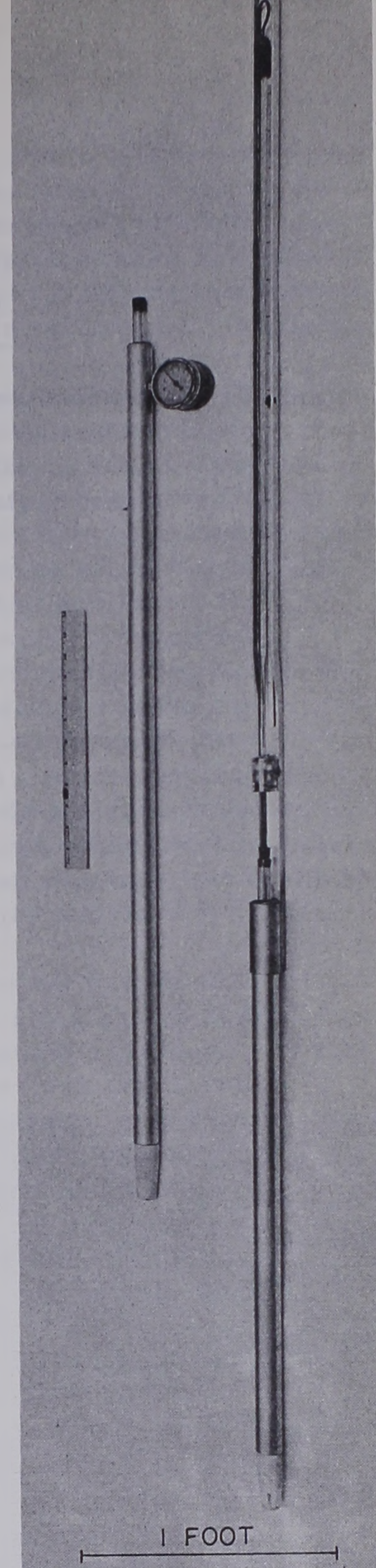


Figure 9.--Types of tensiometers. Left, vacuum gage. Right, manometer.

Nuclear Method

Moisture measurement by the nuclear method depends upon (a) a source of fast neutrons, (b) the slowing down and deflection of these neutrons by the water in soil, and (c) a measure of the resulting slow neutrons. Carlton et al. (22) have stated the theory as follows:

> The measurement of soil moisture is based on the physical laws governing the scattering of neutrons in matter and, in particular, the scattering of neutrons in soil. When a fast neutron source is placed in soil, the emitted neutrons collide with the atoms comprising the soil. As a result of these collisions, the neutrons are scattered in all directions and some of them return to the vicinity of the source. However, in each collision the neutron loses part of its kinetic energy and is slowed down. The average energy loss is much greater in neutron collisions with atoms of low atomic weight than in collisions involving heavier atoms. As a result, the number of slow neutrons found near the source is a function of the number of atoms of low atomic weight present in the soil. If the number of these atoms in the soil is increased, a greater number of slow neutrons will be found near the source.
>
> Hydrogen is the only element of low atomic weight found in ordinary soils in appreciable amounts. Therefore, if a device for detecting slow neutrons is placed in the soil near a fast neutron source, the number of slow neutrons counted per unit of time is a measure of the concentration of hydrogen atoms in the soil. Since the hydrogen is largely contained in molecules of free water (moisture that can be evaporated by heating the soil to a temperature of 110° C.), the slow neutron count is a direct measure of the moisture content of the soil.

The nuclear method gives the amount of water per unit volume of soil. Since the relationship between neutron count and moisture content is largely independent of the character of the soil, it is possible that one calibration curve will suffice for all locations. If moisture content in percent by weight is desired, the soil bulk density must be determined. Nuclear equipment that utilizes gamma rays produced by cobalt 60 has been devised to measure bulk density.

The equipment used in tests at the Vicksburg Project was designed at Cornell University (5, 22). It included a source of fast neu-

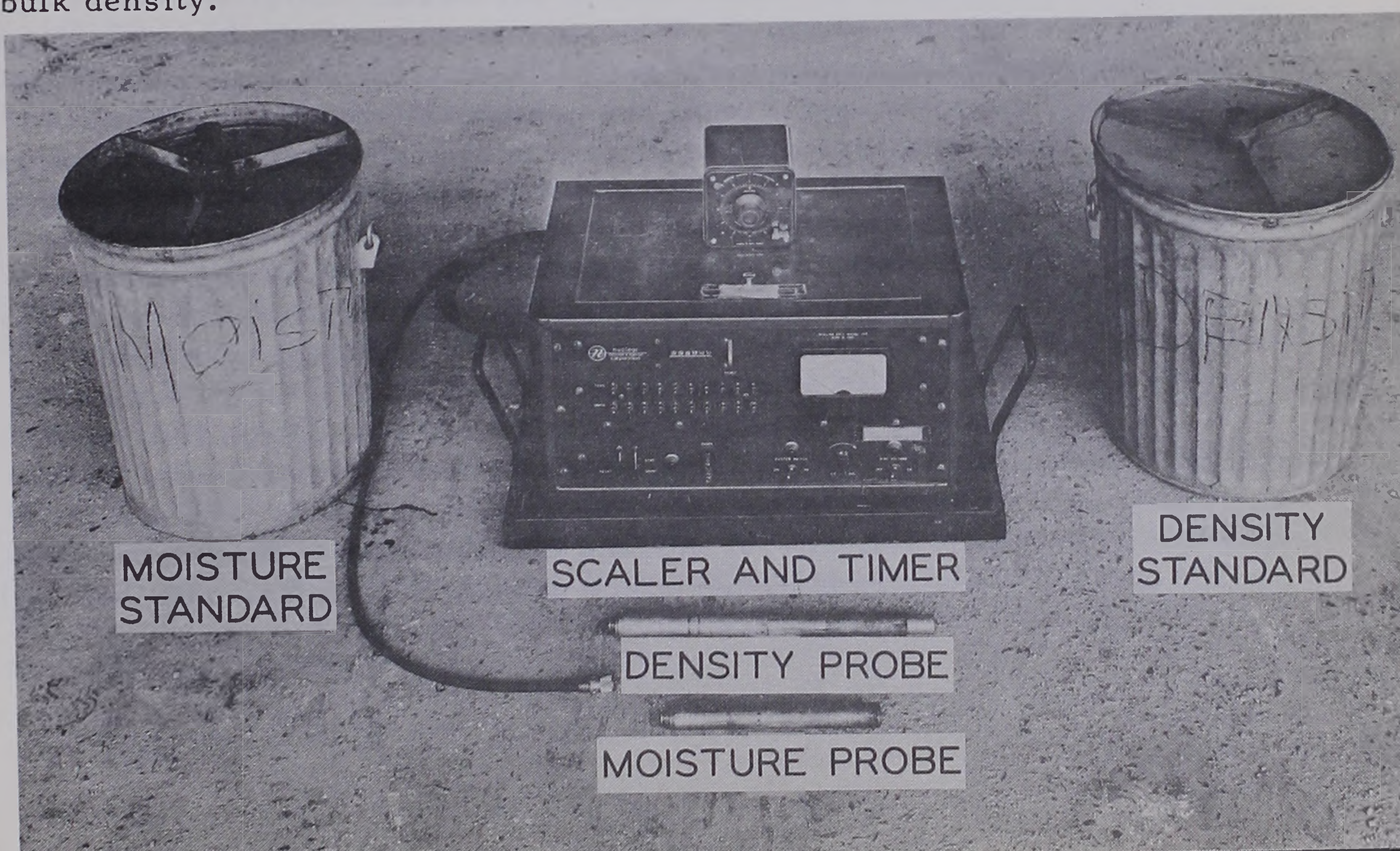
trons (25 millicuries of radium D-beryllium) and a Geiger-Muller counter tube, both sealed within a moisture probe; access tubes which were driven into the ground and into which the moisture probe was lowered; a scaling mechanism for electronically indicating the pulses received from the counter tube; a timer; and a container of water in which standard readings were taken (fig. 10).

The moisture probe, about 9 inches long, was made of thin-walled brass tubing 1 inch in outside diameter. Within the probe, the neutron source and counter tube were separated by a 1-1/2-inch lead plug. Access tubes were made from stainless steel tubing 1-1/16 inches in outside diameter and with a wall thickness of 1/32 inch. One end of each tube was fitted with a metal point. Tubes were 3 and 5 feet long; longer tubes can be used.

A 13-foot length of coaxial cable connected the scaling unit to the moisture probe. A trailer-mounted gasoline-driven generator provided current for field use.

Before readings were taken in the soil, three 3-minute readings were made in the standard. Then the probe was lowered into the access tube in the soil and a series of three 3-minute readings was taken at various depths to 42 inches.

Figure 10.--Nuclear equipment for measuring soil moisture and soil bulk density.



The instrument was calibrated by graphically relating count ratio (count in soil divided by count in standard) to soil-moisture percent by volume as obtained from duplicate soil-tube samples and cylinder bulk-density samples (85). Calibration points of the 1-1/2- and 4-1/2-inch soil depths did not agree with those from lower depths because of loss of radiation at the ground surface. Separate calibration curves, three in all, were developed for the 1-1/2-, the 4-1/2-, and 7-1/2-inch and lower depths (fig. 11).

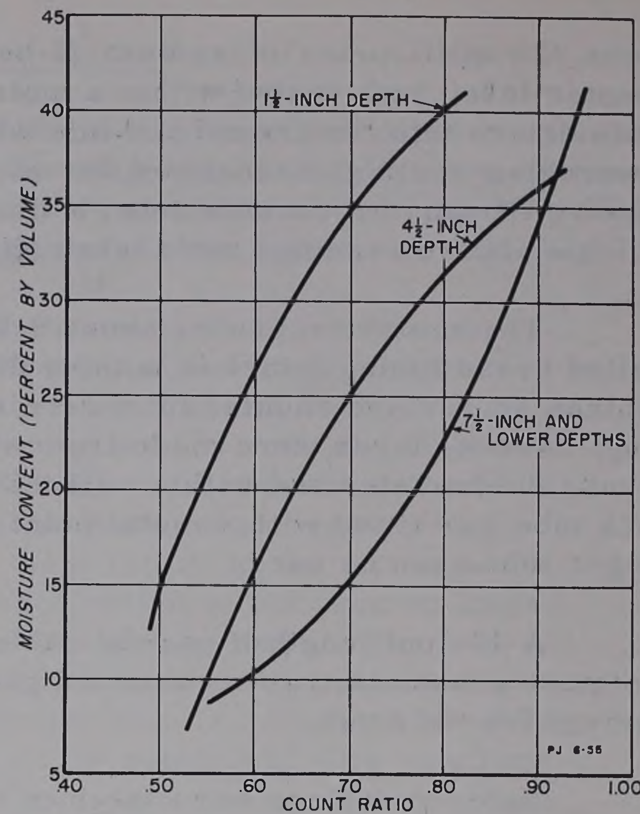


Figure 11.--Sample calibration curves for nuclear equipment.

Fifty-five measured moisture contents for depths from 7-1/2 to 42 inches deviated from the calibration curve by an average of 2.0 percent by volume or about 1.4 percent of the oven-dry weight of the soil. For eleven measurements, the average deviation was 1.4 percent by volume at the 1-1/2-inch depth and 2.0 percent by volume at the 4-1/2-inch depth. With additional experience in handling the equipment, accuracy may be increased.

The above deviations compare well with the findings of others. Carlton et al. report a deviation of 1.3 percent by volume in laboratory tests (22). Using similar equipment, also in the laboratory, investigators at the University of California found an average deviation of 1.4 percent by volume (41), while in a field study at the University of Saskatchewan all deviations were within 3 percent by weight and most were 2 percent or less (45). If an average density of 1.3 grams per cubic centimeter is assumed, 2 percent by weight is equivalent to 2.6 percent by volume.

Portable meter.--Recently, a portable slow-neutron flux meter for measuring soil moisture has been devised by Underwood, van Bavel, and Swanson. This meter has a source-counter assembly which can be inserted in a 2-inch well or, for surface measurements, laid flat on the ground (82). It uses a radium-beryllium source of 10 millicuries nominal

strength and a proportional counter. A 10-foot coaxial cable connects the counter to a battery-operated rate meter which is custom built. A bucket of water, with a central cylinder for insertion of the source-counter assembly, is used as a standard. The weight of the assembled equipment, not including the standard, is less than 20 pounds.

An instrument of this type is now being commercially produced. It is called a "direct soil-moisture determinator."

Evaluation of Methods

Each of the four methods just described has certain advantages and disadvantages. Three of the methods, the electrical-resistance, tensiometer, and nuclear, were devised primarily to give *in situ* records, a distinct advantage for many types of investigations over the gravimetric method, in which the sampling point is destroyed. As will be pointed out later, this is an over-simplification because field calibration recommended for the *in situ* instruments tends to reduce their point significance, lending the data an areal significance not generally appreciated. Too, with sufficient replication, gravimetric sampling can yield records susceptible of point interpretation. Thus, an evaluation of instruments in respect to their *in situ* measuring ability is not too meaningful. The exception is the nuclear method: apparently independent of field calibration, it may with further development prove to give true *in situ* measurements.

In the following sections the methods will be judged as to their accuracy and range, freedom from error due to variations in salt concentration or changes in temperature, ease and speed of measurement, and durability and relative cost of equipment.

Range of Measurement and Accuracy

Electrical-resistance units are most responsive to moisture-content changes from below wilting point to field capacity. The plaster of paris units are not sensitive above field capacity (17). At moisture contents between field capacity and saturation, the resistance change per unit change of moisture for the fiberglas and nylon units is less than at lower moisture levels. Also, field calibration of these units at moisture contents above field capacity is inaccurate because, in sampling, gravitational water may be lost or extraneous free water included. The calibration curve for the nuclear equipment used at Vicksburg tends to level off at very high moisture contents, an indication of decreased accuracy in this range.

Tensiometers are the best method now available for the range of soil moisture from field capacity to saturation. On the other hand, the fact that they cannot be used to measure low moisture contents usually prevents securing continuous records. Slater and Bryant noted that in 1,078 instrument days of measurement in Maryland, the tensiometers were inoperative 73 percent of the time (73).

The accuracy of the various methods is somewhat difficult to evaluate, since rigorous comparisons have never been made. Bouyoucos and Mick stated that the relative experimental error of laboratory-calibrated plaster of paris units was from ± 0.1 to ± 1.0 percent (17). As the blocks are not accurate at high moisture content, and since laboratory calibration curves, from Vicksburg Project experience, do not agree with those derived by field calibration, comparable absolute errors could be expected to be somewhat greater.

In a recent comparison at a Vicksburg site, nuclear equipment and fiberglas units gave very similar accuracy (85). In the nuclear method there was an average deviation of 1.4 percent by weight from the calibration curve. Eight fiberglas units, calibrated in the field, showed an average deviation of 1 percent by weight.

In more than 1,100 observations at three Vicksburg sites, the average deviation of the mean of duplicate gravimetric samples from fiberglas-unit calibration curves was 1.6 percent by weight. Colman and Hendrix (27) measured deviations from a mean calibration curve for five laboratory-calibrated fiberglas units. Deviations were less than 0.5 percent from wilting point to field capacity and about 1 percent above field capacity. Stackhouse and Youker found close agreement between the moisture records of fiberglas-gypsum units and the weighing monolith lysimeter in which they were buried (77).

Plaster of paris blocks, fiberglas units, and nylon units respond with about equal rapidity to changes in soil moisture (55). Comparing plaster of paris and fiberglas units and tensiometers, Ewart and Baver (36) reported that a rapid drop in the resistance of one type of unit was followed by a similar drop in the other. However, the tensiometer was from 40 minutes to 6 hours slower than the other instruments in recording a drop. On the basis of daily readings, Slater and Bryant (73) found response of plaster of paris blocks and tensiometers prompt, with tensiometers more sensitive at higher moisture contents. These authors also noted that tensiometers frequently leak, and thus give inaccurate results.

An undetermined source of error with plaster of paris blocks is the rather high proportion of electrical conduction which follows paths partially outside the block. Slater found that conduction may be confined wholly within the block by locating one electrode centrally in a cylindrical screen that serves as the second electrode (72).

Another source of error in these blocks is hysteresis--i.e., the tendency of the block, at a given soil-moisture tension, to be higher during soil drying than during soil wetting. Tanner and Hanks (80) determined hysteresis over a tension range of 0 to 8 atmospheres and found that unless the blocks are calibrated individually and unless they begin drying from a definite moisture condition, an estimate of soil-moisture tension from block resistance may be in error by an amount equal to 0.5 to 1.0 times the estimated tension. Hysteresis effects in the blocks tended to compensate for moisture hysteresis effects in the soil when blocks were used for moisture-content determination.

Soil-moisture records secured with tensiometers also exhibit considerable hysteresis (64). Richards points out that drying curves are of chief interest in practical agriculture, since the wetting process is usually of short duration (62).

Effect of Salt Concentration

The salt concentration of the soil solution does not affect the gravimetric, tensiometer, or nuclear methods. For the electrical units, it can be the deciding factor as to whether certain types are used.

Ewart and Baver (36) found that increasing the salinity from 0 to 0.2 percent had little or no effect on moisture readings from Bouyoucos blocks. When the concentration was raised to 0.5 percent, drops in resistance were noticeable. Fiberglas units were significantly affected by an increase from 0 to 0.1 percent. The authors concluded that, in mildly saline regions, salt concentrations are not high enough to affect the gypsum block values.

In successive drying cycles during laboratory calibration, Colman and Hendrix (27) found that sufficient salts accumulated from tap water to reduce the resistance of fiberglas units. They recommended that distilled water be used in laboratory calibrations and that units be field-calibrated if they are to be placed in soils varying in soluble salt content during the year.

According to Bouyoucos (11), nylon has virtually no buffering action, but since the units are calibrated for their respective soil this

is not a hardship. Changes in salt concentration within the same soil are considered unimportant under average conditions. For the plaster of paris block, Bouyoucos and Mick report no effect on the moisture content-resistance relation with soil samples containing an equivalent of 1,000 pounds of 4-16-8 fertilizer per acre (17).

Weaver and Jamison found that the resistance of fiberglas, nylon, and plaster of paris units decreased appreciably from tap water and 0.01 to 0.1 normal solution of sodium chloride at tensions between 0 and 15 atmospheres. The three solutions were equal in paste resistance to application of 40, 850, and 1,900 pounds of a commercial 4-10-7 fertilizer per acre 6 inches of topsoil (86).

Effect of Temperature

To secure accurate records with electrical units, resistance must be adjusted to a common temperature. The thermistor in the fiberglas unit makes it possible to measure soil temperature easily. With the other types of units separate temperature-sensing instruments are necessary.

As has been mentioned, temperature gradients between the porous cup of the tensiometer and the surrounding soil may cause a variation in tension readings. Measurements by the gravimetric method are not affected by temperature changes above freezing. The nuclear method reportedly operates independently of temperature (5).

Ease and Speed of Measurement

In effort required to secure frequent soil-moisture measurements, the four methods may be ranked (from most to least laborious) as follows: gravimetric, nuclear, electrical, tensiometer. There is no question that the gravimetric method requires the most effort. To a great extent the total effort required to use electrical units and tensiometers depends on how much gravimetric sampling is necessary for calibration. Once calibrated, both types of instruments are read easily. If the nuclear method will require only one calibration for all soils, it may become the easiest method.

Considering speed of measurement, the same order would be followed. Time required for sampling with a soil tube depends on the condition of the soil. For soils easy to sample, 16 to 25 samples from increasing depths to 4 feet can be taken in about one hour. Under dry conditions, sampling would take twice that long; in stony soils, perhaps a full day. With the nuclear equipment used at the Vicksburg Project,

eight measurements required about two man-hours. Less time is required with electrical-resistance units; in a recent test, 1 minute and 26 seconds were required to read 10 fiberglas units with the ohmmeter and convert readings to moisture contents (55). An average of 4 minutes and 3 seconds was required to read resistances of 10 fiberglas units with the Bouyoucos bridge. According to Bouyoucos and Mick (18), a single reading can generally be taken in less than a minute. Tensiometers, with their indicating mechanism, are most rapidly read.

Durability

All of the commonly used instruments are very durable. Occasionally, the points of soil tubes become worn or chipped and must be replaced. Fiberglas units have been used as long as four years without failure. Until recently, a disadvantage of the plaster of paris blocks was their tendency to dissolve when the soil remained wet for long periods of time. This has been corrected by impregnating these blocks with a nylon plastic resin, a treatment which does not change their physical or chemical characteristics (14). The nuclear equipment tested at Vicksburg frequently broke down.

Relative Cost

All of the methods involve equipment that is commercially produced for soil-moisture measurement. The following current prices will vary from time to time and are only for relative comparison.

Gravimetric sampling	
Five-foot soil tube with hammer	$25.50
Soil auger and open-side tube	13.50
Electrical-resistance method	
Plaster of paris blocks, each	$1.85
Nylon unit (encased in plaster of paris)	3.85
Bouyoucos bridge	200.00
Fiberglas unit	4.60
Alternating-current ohmmeter	160.00
Tensiometer	
One- to 4-foot models	$18 to $22

Radioactive method

Direct soil-moisture determinator (complete with radium-beryllium)	$1,425.00
Equipment described on pages 24-25 (not including generator or radium D-beryllium [3/])	1,000.00

Summary

Selection of instruments will depend on their relative merits as already considered and on proposed frequency of measurement and length of record, experience of personnel, and commonsense.

As a general rule, the gravimetric method should be used unless measurement by one of the indirect methods is absolutely necessary to satisfy study requirements. The gravimetric method requires less experience than any of the others. As it provides direct measurements, the time, effort, and possibility of error associated with converting resistances, tension measurements, or neutron counts to soil-moisture content are avoided. Even if one of the other methods is chosen, numerous gravimetric samplings are usually required for calibration or checking.

Considerable knowledge of the soil-moisture regime may be secured by judicious gravimetric sampling, i.e., selecting sampling dates with regard to weather conditions and making certain that the points and depths sampled will give a maximum of information.

Electrical-resistance instruments are most useful for securing daily records of considerable duration; in this situation the sampling-area disturbance and time and effort involved with the gravimetric method are usually prohibitive. Daily measurement is necessary when moisture content before and after rainfall is needed. If the entire moisture range is to be covered, the fiberglas or nylon-gypsum units are recommended. If temperature corrections are considered necessary, the fiberglas unit should be used. If the soil has been fertilized, increase in salt concentration of the soil solution may prevent satisfactory measurements with electrical units.

Tensiometers are most useful in irrigation studies. Elsewhere the soil is dry too frequently to give them any value.

3/ The radium D-beryllium was rented at $24.00 a month.

Nuclear instruments have not been tested sufficiently to demonstrate their suitability for routine field use; they do hold promise.

Soil-Moisture Expression

Moisture content can be expressed on either a weight or volume basis. On a weight basis, it is almost always given as a percentage of the oven-dry weight of the soil. On a volume basis, it is usually stated as the percentage of the total soil volume occupied by water.

Values in percent by weight are relatively easy to compute:

$$\begin{array}{c}\text{Moisture content} \\ \text{(percent by weight)}\end{array} = \frac{\text{Weight of water in sample x 100}}{\text{Oven-dry weight of soil in sample}}$$

To obtain values in percent by volume, volume measurements are substituted for weight:

$$\begin{array}{c}\text{Moisture content} \\ \text{(percent by volume)}\end{array} = \frac{\text{Volume of water in sample x 100}}{\text{Total volume of sample}}$$

The volume of water in the sample can readily be determined from its weight (1 cubic centimeter equals 1 gram). The volume of the sample, that is, the volume it occupied in the field, can be determined by using cylinders of known size to secure soil samples. Henrie has pointed out that the inches depth of water in a soil sample taken with a soil tube equals the product of the weight of water in grams times $1/2\,D^2$, D being the inside diameter of the cutter in centimeters (39).

Generally, percent by volume can be less accurately and less easily obtained by field measurement than can percent by weight. Therefore the usual practice is to derive percent-by-volume values from percent by weight by using an average bulk density:

$$\begin{array}{c}\text{Moisture content} \\ \text{(percent by volume)}\end{array} = \begin{array}{c}\text{Moisture content} \\ \text{(percent by weight)}\end{array} \times \text{Bulk density}$$

Bulk density, the ratio of the weight of oven-dry soil to the volume it occupied in the field, is generally expressed in grams per cubic centimeter.

Expression of moisture content in percent by weight is satisfactory when moisture contents of soils of similar bulk density are compared. However, values in percent by weight do not indicate how

much water is in the soil. Values on a volume basis are necessary if absolute quantities of moisture content are required or for strict comparisons between soils of different bulk densities. They are very useful in hydrologic studies where soil moisture, precipitation, and streamflow are expressed volumetrically. Percent-by-volume values do, however, possess an added source of error over percent-by-weight, because measurements of soil volume are also involved.

Other Means of Expression

Moisture content of the soil can be expressed in several other ways, all derived from percentages by weight or volume. One of the most common and most generally useful expressions is in inches depth of water--either per inch or foot of soil, or in a given soil horizon, or in the root zone of a specific crop, or in some other specified soil depth. The value in inches depth is easily obtained from the moisture content in percent by volume:

$$\underset{\text{(inches depth)}}{\text{Moisture content}} = \underset{\text{(percent by volume)}}{\text{Moisture content}} \times \underset{\text{(in inches)}}{\text{Soil depth}} \times \frac{1}{100}$$

In crop studies, the term available water is sometimes used. This refers to the water available to plants and is the moisture content of the soil (gravitation water excluded) less the amount remaining at the permanent wilting point. Available water can be expressed in terms of percent by weight, percent by volume, or inches depth. The permanent wilting point must be established for each soil by appropriate field or laboratory measurements.

Sometimes the amount of available water present in the soil at a given time is reported as a percentage of the soil's available water capacity, or the difference between field capacity and wilting point.

Conrad and Veihmeyer (28) proposed the term relative wetness to express the ratio of moisture content to moisture equivalent 4/. This expression enables comparisons of moisture conditions between soils or between soil horizons that differ in texture.

The moisture level in a soil is sometimes given in terms of tension, indicating the force by which the water is held. Tension, or negative pressure, is generally expressed in atmospheres or in centimeters of water; for all practical purposes one atmosphere is equal to 1,000 centimeters. The term pF, the logarithm of the tension in centimeters, has also been used. Moisture tension can be measured

4/ Moisture equivalent is the moisture content of soil that has been subjected to a centrifugal force of 1,000 times gravity.

directly with a tensiometer. To convert tension values to moisture content, a moisture-tension curve must be prepared for individual soils from concurrent laboratory or field measurements of moisture content and tension.

Stoniness

Stone in the soil complicates soil-moisture expression as well as its measurement. Depending upon the amount and size of the stones and objectives of the study, soil-moisture content can be reported as either a percent of total weight or volume inclusive of stones, or as a percent of net weight or volume exclusive of stones. In any case, it should be made clear which method is being used, why it is being used, and, if stone is excluded, the minimum size considered. Degrees of stoniness should be reported in site descriptions. Nikiforoff (51) and the Soil Survey Manual (76) present discussions and classifications of stoniness.

Where soils are stony, moisture content in percent by weight is often related to the net weight of soil. Olson and Hoover (53) suggest that samples with an estimated rock content of 2 percent by weight or greater be screened through a 2-millimeter sieve after the samples have been oven-dried. The weight of the stones is deducted from the oven-dry weight to obtain the net oven-dry weight. Without sieving, the moisture percent by weight will represent the soil exclusive of material too large to be sampled by the equipment used.

Moisture content in percent by volume exclusive of stone can be determined from the corresponding percent-by-weight value and a bulk density value that is also based upon weight and volume determinations exclusive of stone. Percent-by-volume moisture content based on total soil volume including stone is probably more useful. If stones are small enough to be sampled with the soil-moisture and bulk-density equipment being used, no difficulty will be encountered in determining this value. Otherwise, an estimate must be made, for each soil horizon or layer, of the percent of total volume that is occupied by stones larger than the size included in the samples. Hoover, Olson, and Metz (40) determined bulk density exclusive of particles above 2 millimeters in size and then, after determining average stone content for the horizons sampled, adjusted bulk density to prevailing field values.

Bethlahmy (7) presented a method based upon weighing the stones found in each 6-inch soil layer, and dividing their weight by their specific gravity to obtain their volume. With this estimate, moisture

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$$\begin{array}{c}\text{Moisture content}\\\text{(inches depth)}\end{array} = \begin{array}{c}\text{Moisture content}\\\text{(percent by volume)}\end{array} \times \begin{array}{c}\text{Soil depth}\\\text{(in inches)}\end{array} \times \frac{1}{100}$$

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Soil variation, in such properties as texture, structure, organic content, and bulk density, will exist over any area mapped as one soil type. A certain heterogeneity within a mapped soil type may be expected, according to the Soil Survey Manual (76):

> The soil type is a subdivision of the soil series based on the texture of the surface soil. . . . [It] is the lowest and most nearly homogeneous unit in the natural system of classification. A soil type may include defined variations in such characteristics as slope, stoniness, degree of erosion, or depth to bedrock or layers of unconformable material.

The effect of vegetation on soil-moisture variation is least when the area is fully occupied with cover of uniform composition and greatest when the soil is only partially covered--as with row-crops or scattered bunchgrasses or shrubs. Variation in vegetal cover causes differences in interception, stemflow, and transpiration. Soil-moisture content and its variation are thereby influenced.

Uneven disposition of rainfall in the soil profile probably accounts for a major part of soil-moisture variation; variation may be caused by differences in infiltration rates, runoff from parts of the area or run-on from adjacent areas, and gain or loss of water at a given point by subsurface flow. Variation in distribution of rainfall over an area also results in variation in soil-moisture content. Where a water table is present, even minor differences in elevation over an area may result in large differences in soil-moisture content at any given soil depth.

In comparing four methods of soil-moisture measurement, Slater and Bryant (73) studied variation in two soils at Beltsville, Maryland. On each soil, areas 40 feet square were selected for uniformity and divided into plots 10 feet square. The areas were at various times bare, mulched, or covered with bluegrass or Italian ryegrass.

Soil samples, representative of a 4-inch intercept centered at the 6-inch soil depth, were taken in duplicate with a soil tube from each plot about 20 times a season. The standard deviation of moisture sampling within plots was 0.75 percent by weight on Beltsville silt loam and 0.53 percent on Muirkirk sand. These standard deviations include both the real differences in soil moisture on different parts of a single plot and whatever errors may have been made in the determinations.

The Vicksburg Project studied the amount of variation in soil-moisture content of the 0- to 6- and the 6- to 12-inch layers on areas of

apparently homogeneous soil and cover in Mississippi, Louisiana, Arkansas, New Mexico, Colorado, and Wisconsin. Each sampling area contained 40,000 square feet (about 0.92 acre), usually as a 200-foot square. Each area was divided into four blocks, each block into four plots, and each plot into twenty-five sampling squares (10 by 10 feet each). At weekly intervals, two blocks, two plots within each of these blocks, and two squares within each of these plots were randomly selected and gravimetrically sampled. From each selected square, one soil-tube sample was obtained from the 0- to 6-inch depth and one from the 6- to 12-inch depth--a total of 8 samples weekly from each depth. Individual samples averaged about 50 grams, dry weight, of soil. At several of the areas, measurements were made for 10 to 16 weeks during the drier part of the year and again in the wet season. The location of study areas, inclusive dates of sampling, and soil and vegetation characteristics are given in table 2.

For each week of sampling at each site and depth, the variance (s^2) associated with any single sample, taken at random anywhere in

Table 2.--Soil-moisture variation study

Site name and location	Soil texture	Vegetation	Season	Weeks	Period covered
				Number	
Mound Madison Parish, Louisiana	Silty clay	Herbaceous--well stocked	Dry Wet	12 12	August 14 to October 29, 1953 January 14 to April 1, 1954
Durden Warren County, Mississippi	Silt loam	Herbaceous--well stocked	Dry Wet	12 12	August 13 to October 28, 1953 January 13 to April 1, 1954
Radiation Warren County, Mississippi	Silt loam	Herbaceous--well stocked	Dry Wet	12 12	August 13 to October 28, 1953 January 13 to April 1, 1954
Headquarters Ashley County, Arkansas	Silt loam	Forest--70-yr.-old loblolly pine	Dry Wet	12 12	September 4 to November 20, 1953 December 24, 1953, to March 12, 1954
Pine Flat Bernalillo County, New Mexico	Silt loam	Open forest--pinon pine, oak brush, juniper, perennial grasses, and weeds	Dry Wet	12 16	August 28 to November 5, 1953 November 9, 1953, to April 5, 1954
Mesa Mesa County, Colorado	Silt loam	Mountain meadow--sagebrush and herbaceous, 25 percent bare	Dry	10	August 18 to October 19, 1953
Escalante Delta County, Colorado	Silty clay loam	Desert--5 to 10 percent herbaceous, remainder bare	Wet	10	December 21, 1953, to March 1, 1954
Sortek Oneida County, Wisconsin	Silt loam	Herbaceous--timothy grass, well stocked	Dry	12	August 24 to November 16, 1953

the whole "acre", was computed from the individual mean squares (MS):

$$s^2 = \frac{2\text{MS within plots} + \text{MS between plots within blocks} + \text{MS between blocks}}{4}$$

Standard deviations were derived from these variances.

The variance was also partitioned into components: within plots (s_w^2), between plots within blocks (s_p^2), and between blocks (s_b^2). Variances for each area were then averaged for the number of weeks in the study; results are shown in table 3.

One of the most striking features is the variation from site to site and sometimes from season to season within a site. The average standard deviation (square root of the average variance) for the "acre" ranges from 0.09 inch (1.1 percent by weight) to 0.46 inch (5.8 percent) in the 0- to 6-inch depth and from 0.12 inch (1.4 percent) to 0.33 inch (4.1 percent) in the 6- to 12-inch depth. These values are much larger than the 0.75 percent and 0.53 percent of Slater and Bryant (73).

The magnitude of the variation that was encountered can in many cases be related to observed site factors. Escalante, with greatest

Table 3.--Soil-moisture variation at 8 sites

Site name	Season	0- to 6-inch soil depth: Mean moisture content	Average standard deviation (s)	Proportion of total variance: s_w^2	s_p^2	s_b^2	6- to 12-inch soil depth: Mean moisture content	Average standard deviation (s)	Proportion of total variance: s_w^2	s_p^2	s_b^2
		Inches	Inch	Percent	Percent	Percent	Inches	Inch	Percent	Percent	Percent
Mound	Dry	1.42	0.09	78	22	0	1.64	0.15	76	16	8
	Wet	2.58	.20	87	0	13	2.60	.19	100	0	0
Durden	Dry	1.47	.34	33	67	0	1.55	.29	43	57	0
	Wet	2.39	.25	26	41	33	2.39	.14	37	37	26
Radiation	Dry	.74	.13	94	0	6	1.02	.21	56	24	20
	Wet	2.17	.15	76	0	24	2.31	.23	40	19	41
Head-quarters	Dry	.80	.16	70	30	0	.72	.16	89	11	0
	Wet	2.10	.20	63	37	0	2.05	.15	50	32	18
Pine Flat	Dry	.74	.14	58	5	37	.90	.12	61	39	0
	Wet	1.76	.20	51	27	22	1.56	.22	82	0	18
Mesa	Dry	.84	.13	78	5	17	.88	.15	72	0	28
Escal-ante	Wet	.98	.46	67	11	22	.88	.33	68	18	14
Sortek	Dry	1.56	.28	100	0	0	1.53	.33	100	0	0
Mean		...	.23	68	19	13	...	.22	67	20	13

variation at both depths, was characterized by scattered clumps of bunchgrasses; the site in effect was a patchwork of herbaceous and bare areas. This would naturally lead to considerable variation.

Mesa also had unevenly distributed vegetation. However, moisture contents were uniformly low through most of the dry period, and variation was much less than at Escalante.

Vegetation at Pine Flat was mixed pinyon pine, juniper, and herbaceous species. Here, variation was large in the wet season but not so large in the dry period.

Soil at Durden, colluvial in origin, was quite variable. Moisture variation in the dry season was large. In the wet season the variation was much less; the water table at this site was quite close to the surface and, as a result, all samples obtained during this period were more or less uniformly wet.

There was also a considerable difference among the sites in the proportion of the total variation which may be assigned to variation within plots, between plots within blocks, and between blocks. The between-block and between-plot variances were probably a measure of the success achieved in laying out uniform plots. At Mound, Headquarters, and Sortek, the percentage of total variation attributable to variation between blocks was small, ranging up to 18 percent. At Radiation, between-block variation was high during the wet period; this may be the result of considerable slope at this site and possible gradation from one soil type to another. At Durden, variation between blocks during the wet period (as compared to total variation) was much greater than during the dry period. It is likely that slight differences in elevation of the blocks affected distance from water table of the samples secured and resulted in this larger block variation.

At four sites, data were collected in the dry season and again in the wet season. At two of these, Mound and Pine Flat, variation for both depths was much larger in the wet season. For one, Radiation, values for each depth were about the same in both seasons. At Durden, probably because of the water-table influence, variation in the wet period was less than under dry conditions.

The variances and standard deviations so far considered give a measure of the reliability of a single sample in determining the true weekly mean. The actual means determined from 8 samples are of course more reliable. The hypothetical standard deviation of each weekly mean can be determined by dividing the standard deviation by 2.8, the square

root of the number of samples. The result will vary somewhat from the true value because the 8 samples were not completely randomized. Thus if the standard deviation is 0.23 inch, the standard deviation of the weekly mean is only 0. 08 inch.

Sampling in this study was from the upper foot of soil only. In order to get a measure of the variation of deeper layers, analysis was made of the duplicate samples taken from the 6- by 6-foot plots for calibration of fiberglas units at the Mound, Durden, and Radiation sites. Standard deviations in percent by weight of single gravimetric samples are given in table 4. For comparison, corresponding standard deviations

Table 4. --Soil-moisture variation by depth: standard deviation (s) of moisture content of a single gravimetric sample

Soil depth (inches)	Mound		Durden		Radiation		All 3 sites	
	Pairs	s	Pairs	s	Pairs	s	Pairs	s
	Number	Percent by wt.	Number	Percent by wt.	Number	Percent by wt.	Number	Percent by wt.
				Within 6- by 6-foot calibration plots				
0-3	72	2. 0	31	1. 9	12	1. 4	115	1. 9
3-6	72	1. 7	32	1. 1	12	1. 1	116	1. 5
6-9	71	2. 0	31	1. 3	12	1. 4	114	1. 7
9-12	70	2. 1	31	1. 4	12	1. 3	113	1. 8
12-15	42	2. 2	31	1. 6	...	...	73	2. 0
15-18	42	2. 8	31	1. 4	...	...	73	2. 3
12-18	27	2. 4	...	...	12	1. 6	39	2. 2
18-21	40	2. 4	28	1. 6	...	...	68	2. 1
21-24	41	2. 4	29	2. 2	...	...	70	2. 3
18-24	26	2. 3	...	...	12	0. 8	38	1. 9
28-32	58	1. 9	26	1. 2	12	1. 1	96	1. 7
40-44	51	1. 6	24	1. 3	12	1. 4	87	1. 5
All depths	612	2. 1	294	1. 5	96	1. 3	1002	1. 9
				Within 50- by 50-foot plots of variation study				
0-6 (dry period)		1. 0		2. 6		1. 6		
(wet period)		2. 2		1. 7		1. 7		
6-12 (dry period)		1. 7		2. 7		1. 8		
(wet period)		2. 3		1. 0		1. 6		

of samples within the 50- x 50-foot plots of the variation study are given at the bottom of the table.

Variation in the several layers of the upper 4 feet of soil seems to be of the same general magnitude; standard deviations range from about 1 to somewhat over 2 percent by weight. At Mound, standard deviations were appreciably larger for the second foot, mostly because uneven wetting after summer storms caused several large differences between duplicate samples. Variation within the calibration plots was somewhat less than that within the 50- x 50-foot plots of the variation study.

Point Estimates and Area Estimates

In a study using electrical-resistance units, sampling methods will depend on whether the soil-moisture record is to represent the point at which the unit is installed or a larger surrounding area. With the point concept, an attempt is made to determine the moisture content of the soil in contact with the unit. Since this soil cannot be directly sampled in the field without destroying the installation, laboratory calibration is required. Field calibration with sampling plots as small as possible (4 x 4 feet, for example) would approach the point-concept requirements.

The area concept is probably more generally useful in soil-moisture studies. The resistance of the soil-moisture unit is considered an index of the average soil-moisture content of a given soil layer over a calibration area whose size is determined by the objectives of the study. Field calibration by random gravimetric sampling relates the unit's resistance to the average moisture content of the layer. The calibration area should be homogeneous, or nearly so, with respect to soil and vegetation.

Thames[5/] has used the area concept for extending information gained from installations of electrical-resistance units. At Rhinelander, Wisconsin, he related resistances of units installed at one site to moisture contents of gravimetric samples obtained from calibration plots at other sites up to 4 miles distant. Calibration curves were prepared, and, from daily resistance determinations at the first site, a daily record of moisture content at the other sites was secured. Vegetation was similar at sites where fiberglas units had been installed and at corresponding sites without units. Soil texture, however, varied considerably. For

5/ Unpublished study on file at Southern Forest Experiment Station.

example, units in one silt loam site were used to predict moisture at a sandy site.

Relative to the effort required to secure a daily record, accuracies were very encouraging. Except for the extreme case of silt loam and sand, a consistent relationship was found between resistance at the unit installations and moisture content at the corresponding sites without units. Probably the general good agreement was due to similarities of depletion forces and rainfall at the pairs of sites. The need in watershed studies for soil-moisture records, coupled with lack of facilities for installing innumerable soil-moisture stations, points up the necessity of devising short-cut methods such as this.

Another method of securing records over a watershed would be to install electrical-resistance units in as many locations as possible, and then secure frequent (preferably daily) soil-moisture records for each soil horizon. For each soil-cover complex in the watershed, the average depth and the field maximum and field minimum moisture contents of each horizon would also be determined. At any given time, estimates for any soil-cover complex would be made by assuming the moisture content to be at the same relative position between maximum and minimum values as at the most nearly comparable location for which a complete record is available. Soil-moisture content would of course be adjusted for differences in depth of corresponding horizons.

Sampling Design

The character of any specific study will dictate the sampling procedures applicable. Objectives may vary from the determination of mean moisture content for a treated or untreated plot of a few square feet in area to the estimation of the mean value for a given soil-cover complex many acres in extent. Again, comparisons may be desired between areas at one specific time, or a complete soil-moisture record covering several days, months, or years may be required.

Cline (24) discussed the principles of soil sampling, mainly from the standpoint of soil chemistry, and stressed that sampling error is commonly much greater than analytical error. Much of this excellent presentation is equally applicable to sampling for moisture content. Reed and Rigney (58) presented data on the number of positions required to attain specified limits of accuracy in sampling for various properties, mostly chemical, in fields of uniform and non-uniform appearance.

The sampling design will depend in part on how much moisture variation is expected. This variation is of the same general nature as

that associated with soil fertility, timber volume, and numerous other characteristics subject to measurement on an area basis. However, soil-moisture content differs from most other soil or site characteristics in being subject to great change in relatively short periods of time. Samples taken from different parts of an area must ordinarily be secured on the same day in order to be comparable. When samplings are made at different times, it is often hard to determine how much of the moisture content difference is associated with time differences and how much with areal variation.

Soil-moisture content varies vertically and horizontally. Location of samples and determination of mean moisture content should ordinarily be limited to essentially homogeneous soil volumes. Vertically, the soil horizon provides a logical division into separate soil populations. However, especially near the surface, moisture content varies greatly with depth even within horizons. On the Vicksburg Project the surface foot was subdivided into four 3-inch layers for sampling purposes. Because of variation with depth, it is also advisable to obtain sample cores extending from top to bottom of the layer being sampled, especially for layers near the surface.

The dual requirement of determining moisture content through space and time often dictates an intensity and frequency of sampling far above that prescribed by financial limitations. The usual result is that experiments are designed to get the best estimates possible for a given expenditure rather than estimates to any predetermined standard of accuracy. Even so, experimental design should be such that the accuracy of the results can be determined.

In situ methods for determining moisture content enable frequent measurement and avoid difficulties encountered when successive estimates are based upon different samples. Even here, however, areal variation is a problem because of the necessity of obtaining gravimetric samples for field calibration or for checking calibrations.

Random location of samples is the usual procedure when data are to be analyzed statistically. However, according to L. R. Grosenbaugh[6/], "Systematic sampling according to a rectangular grid pattern probably affords the most efficient estimate of the mean volume of water in a specified rectangular space, though of course an element of randomness should govern the initial positioning of the grid, if bias from edge effect is to be avoided. DeLury (31) has provided an interesting and elegant

6/ Personal communication, December 6, 1954.

method for fitting a surface to such a systematic sample, and observed deviations from this surface provide a realistic estimate of error. His simplified computational method allows picking out by inspection the highest degree terms which contribute to a good fit, and residual error can be obtained by simple addition."

The simplest method for sampling moisture consists of obtaining, on a given date, duplicate samples from each soil depth under consideration. Variation between paired samples will give a measure of reliability. Sampling in duplicate was the regular procedure for calibrating fiberglas electrical-resistance units on the Vicksburg Project.

Increasing the number of samples will of course increase the reliability of the mean. If an estimate of the standard deviation (s) of moisture content is obtained, an estimate of the standard deviation of the mean, or standard error ($s_{\bar{x}}$), can be made for any given number of random samples (n):

$$s_{\bar{x}} = \frac{s}{\sqrt{n}}$$

The standard deviation can be estimated if the range between the largest and smallest values in a sample of given size is known. Snedecor (75), in a table based on the work of Tippett and Pearson, gives mean values of range/s. For example, with sample sizes of 2, 5, 10, and 20, range/s equals 1.13, 2.33, 3.08, and 3.73 respectively.

Compositing samples helps to attain increased accuracy for a given sampling effort. Two or more samples procured from a given soil depth by soil tube or other instrument are placed in one container. Thereafter, through weighing, drying, and reweighing, they are handled as one sample. In any series of samplings, enough uncomposited samples should be obtained to give some idea of the magnitude of variation and the reliability of the results from composited samples. Care should be taken not to composite samples from too large an area because there is danger of covering up differences between locations.

Plant spacing, as in orchards, may result in a uniform pattern of soil-moisture variation. Jackson and Weldon (42) developed formulas for determining the weight of water in a soil or subsoil mass in which the moisture content increases with distance from a plant or group of plants. Where plants vary widely in size and are unevenly distributed, as at the Escalante site, the only method for determining mean moisture content is to sample the area as a whole, increasing the sample size in accordance with the amount of variation present.

LITERATURE CITED

(1) Aldous, W. M., Lawton, W. L., and Mainport, R. C.
1952. The measurement of soil moisture by heat diffusion. Civil Aeronautics Admin. Tech. Devel. Rpt. 165.

(2) Allyn, R. B.
1942. A calibrated soil probe for measuring field soil moisture. Soil Sci. 53: 273-285.

(3) ________ and Work, R. A.
1941. The availameter and its use in soil moisture control:
I. The instrument and its use. Soil Sci. 51: 307-321.
II. Calibration methods. Soil Sci. 51: 391-406.

(4) Begemann, E.
1936. Determination of the water content of soil samples by means of xylol. Proc. Internatl. Conf. Soil Mech. and Found. Engin. 2: 66-67.

(5) Belcher, D. J., Cuykendall, T. R., and Sack, H. S.
1950. The measurement of soil moisture and density by neutron and gamma ray scattering. Civil Aeronautics Admin. Tech. Devel. Rpt. 127.

(6) Bethlahmy, N.
1951. An alinement chart for use with the fiberglas soil-moisture instrument. Soil Sci. 71: 377-380.

(7) ________
1952. A method for approximating the water content of soils. Trans. Amer. Geophys. Union 33: 699-706.

(8) Bidwell, G. L., and Sterling, W. F.
1925. Preliminary notes on the direct determination of moisture. Jour. Assoc. Off. Agr. Chemists 8: 295-301.

(9) Bouyoucos, G. J.
1931. The alcohol method for determining moisture content of soils. Soil Sci. 32: 173-179.

(10) ________
1937. Evaporating the water with burning alcohol as a rapid means of determining moisture content of soils. Soil Sci. 44: 377-381.

(11) Bouyoucos, G. J.
1949. Nylon electrical resistance unit for continuous measurement of soil moisture in the field. Soil Sci. 67: 319-330.

(12) ________
1950. A practical soil moisture meter as a scientific guide to irrigation practices. Agron. Jour. 42: 104-107.

(13) ________
1952. Improvements in the nylon method of measuring soil moisture in the field. Agron. Jour. 44: 311-314.

(14) ________
1953. More durable plaster of paris moisture blocks. Soil Sci. 76: 447-451.

(15) ________
1954. New type electrode for plaster of paris moisture blocks. Soil Sci. 78: 339-342.

(16) ________
1954. Newly developed nylon units for measuring soil moisture in the field. Highway Res. Abs. 29-32.

(17) ________ and Mick, A. H.
1940. An electrical resistance method for the continuous measurement of soil moisture under field conditions. Mich. Agr. Expt. Sta. Tech. Bul. 172.

(18) ________ and Mick, A. H.
1947. Improvements in the plaster of paris absorption block electrical resistance method for measuring soil moisture under field conditions. Soil Sci. 63: 455-465.

(19) Broadfoot, W. M.
1954. Procedures and equipment for determining soil bulk density. U. S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 135, pp. 2-11.

(20) Carlson, C. A.
1953. Moisture equilibration in natural cores during laboratory calibration of fiberglas soil-moisture units. U. S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 128, pp. 31-39.

(21) Carlson, C. A.
1954. Comparison of laboratory and field calibration of fiberglas moisture units. U.S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 135, pp. 34-42.

(22) Carlton, P. F., Belcher, D. J., Cuykendall, T. R., and Sack, H. S.
1953. Modifications and tests of radioactive probes for measuring soil moisture and density. Civil Aeronautics Admin. Tech. Devel. Rpt. 194.

(23) Carter, C. E.
1938. A field method for determining soil moisture. Austral. Forestry 3: 15-16.

(24) Cline, M. G.
1944. Principles of soil sampling. Soil Sci. 58: 275-288.

(25) Coile, T. S.
1953. Moisture content of small stone in soil. Soil Sci. 75: 203-207.

(26) Colman, E. A.
1946. The place of electrical soil-moisture meters in hydrologic research. Trans. Amer. Geophys. Union 27: 847-853.

(27) ________ and Hendrix, T. M.
1949. The fiberglas electrical soil-moisture instrument. Soil Sci. 67: 425-438.

(28) Conrad, J. P., and Veihmeyer, F. J.
1929. Root development and soil moisture. Hilgardia 4: 113-134.

(29) Davis, W. E., and Slater, C. S.
1942. A direct weighing method for sequent measurements of soil moisture under field conditions. Jour. Amer. Soc. Agron. 34: 285-287.

(30) Davisson, B. S., and Sivaslian, G. K.
1918. The determination of moisture in soils. Amer. Soc. Agron. Jour. 10: 198-204.

(31) DeLury, D. B.
1950. Values and integrals of the orthogonal polynomials up to $\underline{n}$ = 26. Univ. Toronto Press, Toronto, Ont., 33 pp.

(32) Diebold, C. H.
1953. Rapid methods for estimating readily available moisture and bulk density of medium- to fine-textured soils. Agron. Jour. 45: 36-37.

(33) Dimbleby, G. W.
1954. A simple method for the comparative estimation of soil water. Plant and Soil 5: 143-154.

(34) Doss, B. D., and Broadfoot, W. M.
1954. Terminal panel for electrical soil-moisture instruments. U.S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 135, pp. 30-31.

(35) Emmert, E. M.
1937. A rapid method for determining soil moisture. Soil Sci. 43: 31-36.

(36) Ewart, G. Y., and Baver, L. D.
1951. Salinity effects on soil moisture-electrical resistance relationships. Soil Sci. Soc. Amer. Proc. (1950) 15: 56-63.

(37) Ferguson, E. R., and Duke, W. B.
1954. Devices to facilitate King-tube soil-moisture sampling. U.S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 135, pp. 26-29.

(38) Haise, H. R., and Kelley, O. J.
1950. Causes of diurnal fluctuations of tensiometers. Soil Sci. 70: 301-313.

(39) Henrie, J. O.
1950. A direct method of computing and correcting the equivalent depth of water. Agr. Engin. 31: 290-291.

(40) Hoover, M. D., Olson, D. F., Jr., and Metz, L. J.
1954. Soil sampling for pore space and percolation. U. S. Forest Serv. Southeastern Forest Expt. Sta. Sta. Paper 42.

(41) Horonjeff, R., Goldberg, I., and Trescony, L. J.
1954. The use of radioactive material for the measurement of water content and density of soil. Presented at the Sixth Ann. Street and Hwy. Conf., Univ. of Cal.

(42) Jackson, M. L., and Weldon, M. D.
1939. Determination of the weight of water in a soil or subsoil mass in which the moisture content increases with distance from a plant or group of plants. Jour. Amer. Soc. Agron. 31: 116-127.

(43) Keen, B. A.
1931. The physical properties of the soil. Longmans, Green, and Co., Inc., 380 pp.

(44) Korty, B. L., and Kohnke, H.
1953. Recording soil moisture automatically. Soil Sci. Soc. Amer. Proc. 17: 307-310.

(45) Lane, D. A., Torchinsky, B. B., and Spinks, J. W. T.
1952. Determining soil moisture and density by nuclear radiations. Symposium on the use of radioisotopes in soil mechanics. Amer. Soc. for Testing Materials, Spec. Tech. Pub. 134, pp. 23-34.

(46) LeCompte, S. B., Jr.
1952. An instrument for measuring soil moisture. New Jersey Hort. News.

(47) Livingston, B. E., and Koketsu, R.
1920. The water-supplying power of the soil as related to the wilting of plants. Soil Sci. 9: 469-485.

(48) Lutz, H. J.
1944. Determination of certain physical properties of forest soils. I: Methods utilizing samples collected in metal cylinders. Soil Sci. 57: 475-487.

(49) Mackaness, F. G., and Rowse, R. W.
1954. Equipment for installing gypsum moisture blocks. Agr. Engin. 35: 337.

(50) Momim, A. H.
1947. A new simple method of estimating the moisture content of soil in situ. Indian Jour. Agr. Sci. 17: 81-85.

(51) Nikiforoff, C. C.
1948. Stony soils and their classification. Soil Sci. 66: 347-363.

(52) Noyes, H. A., and Trost, J. F.
1920. Determination of moisture in field samples of soil. Jour. Assoc. Off. Agr. Chemists 4: 95-97.

(53) Olson, D. F., Jr., and Hoover, M. D.
1954. Methods of soil moisture determination under field conditions. U. S. Forest Serv. Southeastern Forest Expt. Sta. Sta. Paper 38.

(54) Palpant, E. H.
1953. An inserter for fiberglas soil-moisture units. U. S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 128, pp. 16-20.

(55) ________ and Lull, H. W.
1953. Comparison of four types of electrical resistance instruments for measuring soil moisture. U. S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 128, pp. 2-15.

(56) ________, Thames, J. L., and Helmers, A. E.
1953. Switch shelters for use with soil-moisture units. U. S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 128, pp. 21-30.

(57) Papadakis, J. S.
1941. A rapid method for determining soil moisture. Soil Sci. 51: 279-281.

(58) Reed, J. F., and Rigney, J. A.
1947. Soil sampling from fields of uniform and nonuniform appearance and soil types. Jour. Amer. Soc. Agron. 39: 26-40.

(59) Reinhart, K. G.
1953. Installation and field calibration of fiberglas soil-moisture units. U. S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 128, pp. 40-48.

(60) ________
1954. Relation of soil bulk density to moisture content as it affects soil-moisture records. U. S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 135, pp. 12-21.

(61) Richards, L. A.
1942. Soil moisture tensiometer materials and construction. Soil Sci. 53: 241-248.

(62) ________
1949. Methods of measuring soil moisture tension. Soil Sci. 68: 95-112.

(63) ________ and Gardner, W.
1936. Tensiometers for measuring the capillary tension of soil water. Jour. Amer. Soc. Agron. 28: 352-358.

(64) Richards, S. J.
1938. Soil moisture content calculations from capillary tension records. Soil Sci. Soc. Amer. Proc. 3: 57-64.

(65) Rowe, P. B., and Colman, E. A.
1951. Disposition of rainfall in two mountain areas of California. U.S. Dept. Agr. Tech. Bul. 1048, 84 pp.

(66) Rowland, E. F., Fagan, T. D., and Crabb, G. A., Jr.
1954. A slide rule for soil moisture determinations. Jour. Amer. Soc. Agr. Engin. 35: 163-164.

(67) Russell, M. B.
1950. A simplified air-picnometer for field use. Soil Sci. Soc. Amer. Proc. (1949) 14: 73-76.

(68) Russell, Sir E. J.
1950. Soil conditions and plant growth. Longmans, Green and Co., Inc.

(69) Scofield, C. S.
1945. The measurement of soil water. Jour. Agr. Res. 71: 375-402.

(70) Sen, A.
1936. Rapid determination of soil moisture by drying the soil over Bunsen burner. Indian Jour. Agr. Sci. 6: 1076-1080.

(71) Shaw, B., and Baver, L. D.
1939. Heat conductivity as an index of soil moisture. Jour. Amer. Soc. Agron. 31: 886-891.

(72) Slater, C. S.
1942. A modified resistance block for soil moisture measurement. Jour. Amer. Soc. Agron. 34: 284-285.

(73) ________ and Bryant, J. C.
1946. Comparison of 4 methods of soil moisture measurement. Soil Sci. 61: 131-155.

(74) Smith, A., and Flint, F. W.
1930. Soil moisture determination by the alcohol method. Soil Sci. 29: 101-107.

(75) Snedecor, G. W.
1946. Statistical methods. (Ed. 4.) Iowa State College Press, 485 pp.

(76) Soil Survey Staff.
1951. Soil survey manual. U.S. Dept. Agr. Handb. 18, 503 pp.

(77) Stackhouse, J. M., and Youker, R. E.
1954. Evaluation of the accuracy of fiberglas-gypsum blocks for measuring soil moisture changes. Agron. Jour. 46: 405-407.

(78) Stoeckeler, J. H.
1937. Measuring soil moisture in the forest nursery. U.S. Forest Serv. Lake States Forest Expt. Sta. Mimeo.

(79) Stout, G. J., and Holben, F. J.
1946. Simple method for rapid drying of soil moisture samples. Amer. Soc. Hort. Sci. Proc. 47: 238.

(80) Tanner, C. B., and Hanks, R. J.
1952. Moisture hysteresis in gypsum moisture blocks. Soil Sci. Soc. Amer. Proc. 16: 48-51.

(81) Uhland, R. E.
1951. Rapid method for determining soil moisture. Soil Sci. Soc. Amer. Proc. 15: 391-393.

(82) Underwood, N., van Bavel, C. H. M., and Swanson, R. W.
1954. A portable slow neutron flux meter for measuring soil moisture. Soil Sci. 77: 339-340.

(83) Van Bavel, C. H. M., and Gilbert, M. J.
1954. Discussion of "A method for approximating the water content of soils" by N. Bethlahmy. Trans. Amer. Geophys. Union 35: 168-169.

(84) Veihmeyer, F. J.
1929. An improved soil-sampling tube. Soil Sci. 27: 147-152.

(85) Waterways Experiment Station, Corps of Engineers
1955. Field tests of nuclear instruments for the measurement of soil moisture and density. Misc. Paper 3-117, 26 pp.

(86) Weaver, H. A., and Jamison, V. C.
1951. Limitations in the use of electrical resistance soil moisture units. Agron Jour. 43: 602-605.

(87) White-Stevens, R. H., and Jacob, W. C.
1940. The rapid detection of soil moisture. Amer. Soc. Hort. Sci. Proc. 37: 261-266.

(88) Whitney, M. A.
1894. Instructions for taking samples of soil for moisture determination. U.S. Dept. Agr., Div. Agr. Soils, Cir. 2.

(89) ________
1896. Methods of the mechanical analysis of soils and of the determination of the amount of moisture in soils in the field. U.S. Dept. Agr., Div. Agr. Soils, Bul. 4.

(90) ________
1896-1899. Report of the Chief of the Division of Agricultural Soils. From annual reports of the Secretary of Agriculture.

(91) Wilson, J. D.
1927. The measurement and interpretation of the water-supplying power of the soil with special references to lawn grasses and some other plants. Plant Physiol. 2: 385-440.

(92) Woods, F., and Hopkins, W.
1954. Phone-jack terminals for soil-moisture units. U. S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 135, pp. 32-33.

(93) Youker, R. E., and Dreibelbis, F. R.
1951. An improved soil-moisture measuring unit for hydrologic studies. Trans. Amer. Geophys. Union 32: 447-449.